WADC TECHNICAL REPORT 55-56
PART II

PROTECTIVE SHOT PEENING OF PROPELLERS

Part II. Fatigue Tests

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LESSELLS AND ASSOCIATES, INC.

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PROPELLER LABORATORY
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WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
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FOREWORD

This report was prepared by Lessells and Associates, Inc., Boston Massachusetts, under U. S. Air Force Contract No. AF 33(616)-2324, Task No. 33048, Project No. 3346, "Propeller Blades." The contract was administered under the direction of the Propeller Laboratory, Directorate of Laboratories, Wright Air Development Center, by Mr. John S. Keeler and Mr. Marshall W. Baldwin. The author wishes to acknowledge the assistance of Mr. L. E. Babcock who designed the fatigue machine used for these tests.

ABSTRACT

This report is the second of two reports covering work performed under Contract No. AF33(616)-2324 during the period from 1 February 1954 to 31 August 1955. The object of the investigation was to determine any benefits of shot peening as a means of protecting aircraft propeller blades against the reduction of fatigue strength arising from surface damage. The first report covered the investigation of the residual stresses induced by each of a variety of shot peening conditions on several materials. The second report covers Prot fatigue tests on SAE 4340 steel specimens which had been shot peened and subjected to simulated propeller blade damage.

The results indicate that shot peening acts as a barrier to the detrimental effects of surface damage. SAE 4340 specimens of hardness R_c51 which were peened before damage showed an average endurance limit 110% higher than those which were not peened prior to damage. Under similar conditions, specimens of hardness R_c31 and R_c41 showed increases in endurance limit of 30% and 87%, respectively.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

John O. Schulze
JOHN O. SCHULZE
Chief, Structures Branch
Propeller Laboratory
Directorate of Development

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I. INTRODUCTION

Aircraft propeller blades, like many aircraft parts, are subjected to large numbers of alternating loads during operation. Their design strength, therefore, must be based upon fatigue strength rather than on other criteria of failure. Propeller blade design is further complicated by the fact that the blades are commonly subjected to surface damage by the impingement of foreign objects such as bits of macadam runway, etc. The sites of this damage act as stress raisers which encourage fatigue failure. Other effects, such as cold work, are present and are difficult to analyze, but the general result of this damage is a reduction in the fatigue properties of the propeller blades. In order to ensure safety, either the propeller must be designed at low stress levels, with consequent inefficient utilization of material, or the blades must be subjected to frequent inspection and rework. These procedures are expensive in time or in aircraft efficiency if safety is to be maintained.

Considerable thought has been given to methods of armoring the propeller blades against damage caused by these foreign objects. Among the ideas presented is the possibility of introducing compressive residual stresses into the blade surfaces. This procedure has received common acceptance as a means for increasing the fatigue strength of many materials (1, 2).* It has been suggested that this procedure might be capable of masking the detrimental effects of surface damage. It was postulated that the damage would not have detrimental effects on surfaces containing residual compressive stresses of sufficient depth and magnitude as to be partially retained even after surface damage.

Of the several available methods for introducing compressive surface stresses, shot peening is probably the most common and most easily applied to propeller blades. It was, therefore, selected for the present investigation.

The first phase of this investigation consisted of a detailed study in which the residual stresses resulting from each of a wide variety of shot-peening treatments were measured. This information was necessary for application to propellers and could be useful in a wide variety of other applications. The details and results of this study are given in Reference (3).

The second phase of the investigation was directed toward the evaluation of shot peening in connection with surface damage. Fatigue tests were performed on specimens which had been subjected to various shot-peening treatments and subsequently damaged. Details of the procedure are given in succeeding paragraphs.

* Numbers in Parenthesis Refer to Bibliography

II. PROCEDURE

SPECIMENS

Fatigue test specimens were of SAE 4340 aircraft quality alloy steel. The material was forged into rough bars 2 1/2 in. wide by 3/8 in. thick by 6 ft long. Test specimens cut from these bars were 1 in. wide by 0.250 in. thick by 15 in. long. The 0.250 in. thickness was rough ground about .010 in. oversize, the bars heat-treated, then finish ground and polished to final dimensions. A 45^{o} by 1/16 in. chamfer was provided at the corners.

As delivered, the bars had been normalized and annealed. After rough machining, they were oil quenched from $1475^{o}F$ and drawn to three levels of tensile strength of about 130,000 psi, 190,000 psi and 260,000 psi. Tensile test results are given in Table 1. Composition, as certified by the supplier, is given in Table 2.

TABLE 1

TENSILE TEST RESULTS

Note: Each number represents the average of 5 specimens

Material	Hardness	Yield Pt. (psi)	Ultimate Strength (psi)
SAE 4340 (Heat E69643)	$52R_c$	226,000	257,000
SAE 4340 (Heat E69643)	$41R_c$	174,000	187,000
SAE 4340 (Heat E69643)	$30R_c$	107,000	131,000

TABLE 2

ANALYSIS OF TEST MATERIAL

SAE 4340 Heat No. E69643

C	Mn	P	S	Si	Ni	Cr	Mo
.40	.76	.010	.016	.24	1.75	.85	.24

Most of the tests were performed on the 190,000 psi steel, using several different peening treatments. The plan here was to study a variety of peening treatments on a single hardness of material, determining any benefits of the treatment and establishing values of peening variables which resulted in the greatest benefit. The results on the single hardness were then used to predict optimum peening treatments for the harder and softer specimen. A single peening treatment was used on each of the latter hardnesses.

Table 3 lists the specimens and their peening depths. Failure stresses are also included here for convenience. Depth of compression refers to the depth of residual compressive stress existing prior to surface damage. This is further explained in the section on shot peening. The shot peening treatments used to obtain these depths are given in Table 4. Residual stress patterns resulting from these treatments can be obtained from Reference (3).

SHOT PEENING

The various peening conditions were set up on the basis of depth of residual stress as it seemed reasonable that the relation between depth of residual stress and depth of surface damage would be a significant parameter. The depth of the layer of compressive stress was chosen as the measure of depth of residual stress. This is defined as the distance from the metal surface to the plane at which the residual stress changes from compression to tension. This distance showed a high degree of consistency in the residual stress studies (Reference 3). Scatter in this parameter was less than the scatter in value of surface stress and in maximum stress.

All peening was done at high coverage, defined here as four times the duration of peening required to cover 98% of the surface of the specimen. Details of peening procedure and equipment are given in Reference (3) but can be briefly described as follows: An air blast cabinet was modified so that the rate of shot flow could be controlled. A reciprocating table was provided for transport of the specimen through the shot stream. Control of peening intensity was obtained through variations in nozzle size, air pressure, shot size, shot flow rate, and number of passes through the shot stream at a constant velocity of 10 in. per minute.

Actual peening conditions for each specimen were determined by selecting a desired depth, then obtaining the necessary conditions from Reference (3). The central 6-in. length of each bar was peened on both sides, except in the case of the highest strength bars. In the latter, it was necessary to peen the entire length in order to avoid fracture outside the peened section.

SIMULATED BLADE DAMAGE

Surface damage was introduced into the specimens (except those tested in the parent condition) in order to simulate service aircraft conditions. This process was performed on a special machine at the Propeller Laboratory, Wright Air Development Center. Figure 1 is a schematic of this device. A steel club propeller about 5 ft long and averaging about 3 in. wide is rotated by a large electric motor. Attached to one end of the club is a piece of glass about 3 in. by 1 in. by 1/4 in. With the motor running at speed, about 2400 rpm, a solenoid places an obstruction in the path of the glass. This causes pieces of broken glass to take up paths tangential to the arc of rotation where they strike fatigue test specimens on a nearby stand. Each specimen was subjected to 10 cycles of this treatment on either side. Ten specimens were placed on the stand simultaneously, their relative positions being rotated between runs, such that the damage was identical insofar as possible.

FATIGUE TESTING MACHINE

The machine used for these tests was specially constructed to enable testing of the specimens by the Prot (4, 5) accelerated method. The specimens were magnetically excited in the fundamental free-free bending mode. For these bars this mode was at a frequency of about 230 cycles per second. Electronic controls were provided to maintain the required stress. In order to provide the control circuits with information of the stress level, a small accelerometer was attached near one end of the specimen. The accelerometer output was calibrated with respect to the optically-determined deflection

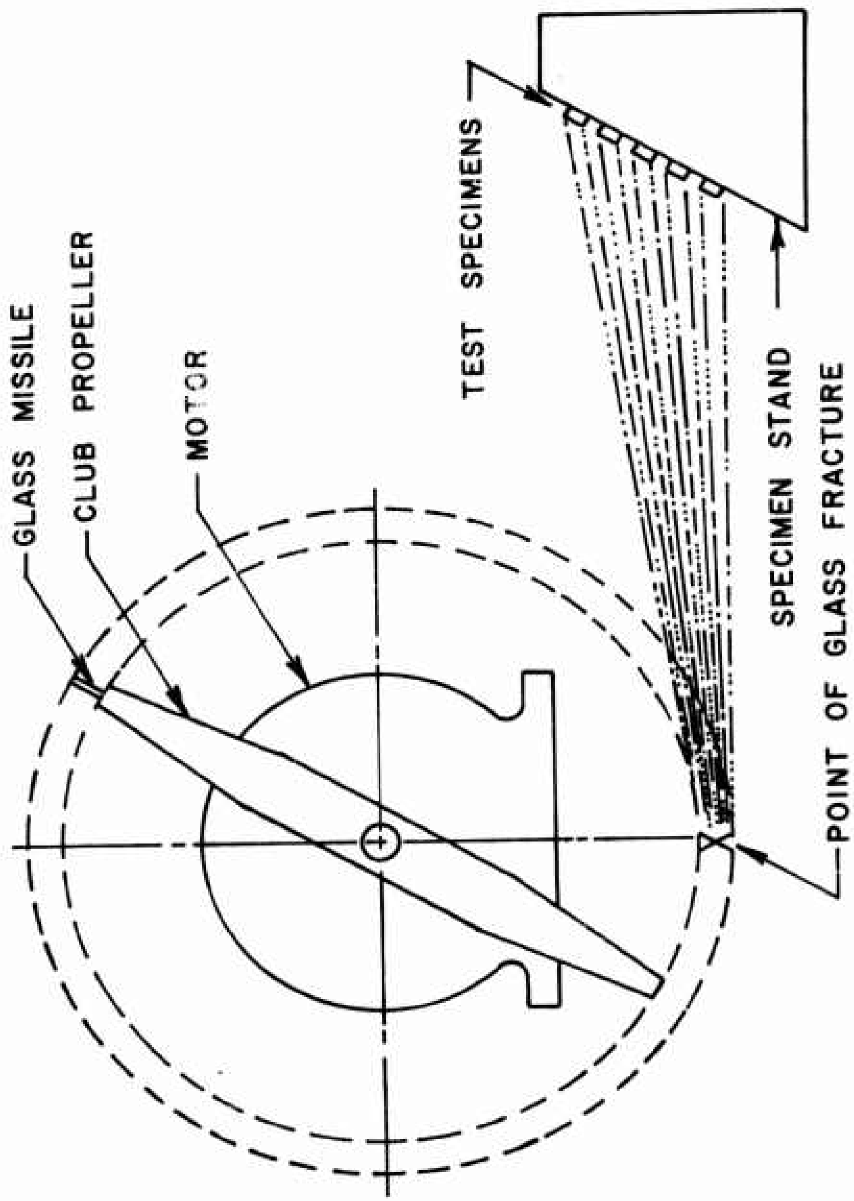

FIGURE 1. SCHEMATIC OF DAMAGING APPARATUS

amplitude of the specimen at its midpoint. An alternative arrangement consisted of a linear deflection-sensitive transducer placed adjacent to the midpoint of the specimen. This eliminated the necessity for making attachments directly to the specimen. Both arrangements worked satisfactorily.

Controls of the machine could be set so as to provide a continuously increasing amplitude of vibration at any desired rate. Specimen failure was detected by reduction in natural frequency. This phenomenon was used to control the automatic shutoff. In this regard, it might be mentioned that the earliest indication of failure was an audible ring of about 6000 cycles per second. This was presumed to be a longitudinal acoustical wave excited in the bar by the impact of the sides of a crack against each other.

Figure 2 is a photograph of the fatigue machine. At the right a test specimen is shown in position for testing. It is supported at its nodal points. Electromagnets supplying the power for deflection are just below each end of the specimen. At the left in Figure 2 is the cabinet containing the excitation power supply and controls.

METHOD OF TEST

Because of the comparative nature of the tests and the number of specimens involved, the fairly high value of 0.04 psi per cycle was used as the rate of stress increase in most instances. It was not possible to run enough tests to establish the Prot slope (5) of failure stress vs. $\sqrt{\alpha}$ (α = rate of stress increase in psi per cycle). Therefore, other sources of data on SAE 4340 were applied in estimating endurance limits from the failure stresses obtained.

The shape of the vibrating bar was assumed to be as follows:

$$y = a(1.153 \cos 4.73 \frac{X}{L} - 0.153 \cosh 4.73 \frac{X}{L}) \cos wt$$

where: y = displacement from quiescent condition (inches)

a = displacement at midpoint of specimen (inches)

X = distance from midpoint (inches)

L = total length (inches)

w = frequency (radians per second)

t = time (seconds)

This assumption, together with assumption of Hooke's Law leads to the following relation between midpoint amplitude and stress.

$$S = 14.61 \frac{EaT}{L^2}$$

where: S = Stress at midpoint (psi)

E = Young's Modulus

T = Thickness of flat bar specimen

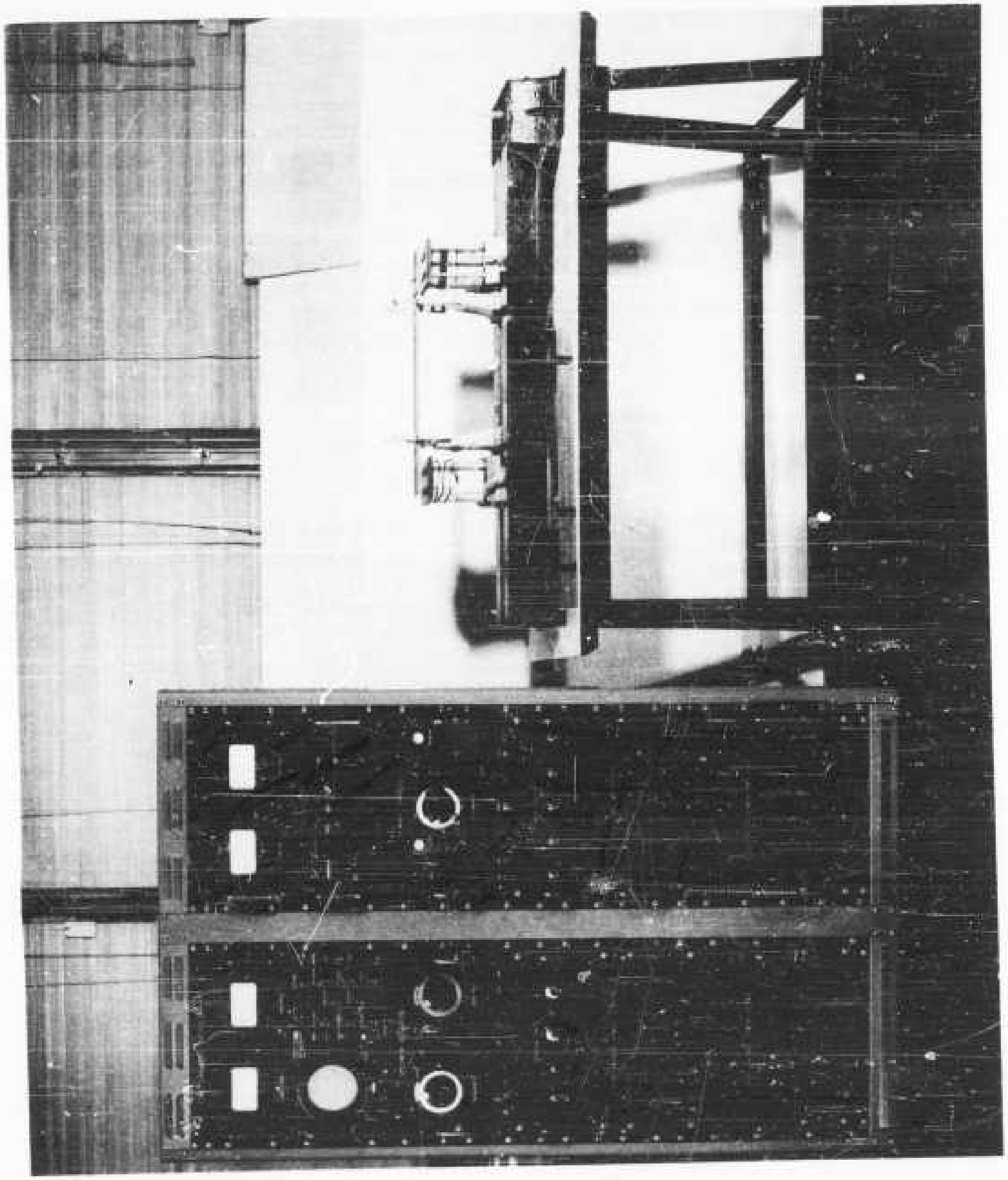

FIGURE 2. RESONANT BENDING FATIGUE MACHINE

Strain gage measurements at the midpoint of the bar were in good agreement with the above relation.

Figure 3. Apparatus for Gouge Depth Measurement

Testing was carried either to the point where the audible indication of cracking was apparent or until the machine shut down because of a drop in bar frequency. Cracks were well developed under the latter condition. These two conditions occurred within a few thousand cycles, indicating rapid crack growth. Growth was more rapid at the higher failure stresses and was extremely rapid in the high strength steel where only about one thousand cycles elapsed between the first audible indication of cracking and complete fracture of the specimen.

After testing, the failures were examined. In the cases where failure originated at a simulated gouge, the gouge depth was measured optically by means of a microscope with a dial gage mounted between the barrel and the stage. This arrangement is shown in Figure 3. In the case of shallow gouges a metallurgical microscope with a 6 mm objective and micrometer screw was used for increased accuracy. Accuracy of gouge depth measurement decreased with increasing peening intensity because of the rough surface. It was impossible to observe gouges on many of the heavily peened specimens, much less measure their depths. Photographs of the cracks were taken in many cases. Where necessary, specimens were bent to a small permanent set in order to delineate the cracks.

Nominal failure stresses were corrected for location along the bar and for the depth of the gouge at which failure occurred. An attempt was made to correlate failure with the type of damage. This was only partially successful, as discussed in succeeding paragraphs.

III. RESULTS

Failure stresses of all specimens are given in Table 3. Individual test points for each group of specimens are plotted in Figures 4 through 14. Endurance limits are obtained by extrapolation to zero rate of stress increase.

As noted, the slope of the extrapolation is assumed to be that reported in Reference (6). The 95% confidence limits are extrapolated at the same slope, although it should be realized that they may be in error near the zero ordinate.

Figure 15 is a summary of results for the 190,000 psi steel. From this plot it can be seen that nearly a 50% improvement over the unpeened damaged condition arises from the shot peening. Under the conditions of damage attained in these tests there appears to be an optimum depth of compression of about 0.015 in., beyond which the strength is slightly reduced from maximum. This reduction is probably a result of surface roughness caused by extremely heavy shot peening. Even at the lightest peening treatment, an improvement of about 30% was obtained. This light treatment had the appearance of a burnished surface, with only very slight surface roughness.

In order to indicate the benefits of peening on a dimensionless basis, Figure 16 is included. In this figure the parameter of depth of compression over depth of damage is used. It appears that a value of five for this ratio represents the maximum attainable improvement over the unpeened case. However, even a ratio of two represents a considerable improvement.

Figures 17 and 18 show the degree of improvement for the 130,000 psi and 260,000 psi steel, respectively. In selecting the single depth of compression to be used in the 130,000 psi steel, and similarly in the 260,000 psi steel, an attempt was made to establish a ratio of five for depth of compression over depth of damage. Although the depth of compression could be controlled quite accurately, it was necessary to extrapolate depth of damage from data on the 190,000 psi specimens. This depth was estimated on the basis of the relative depths of a spherical hardness indentor in the different materials. Actual measurement of damage depth was somewhat inaccurate in the case of the very hard specimens, since the depths were very small. Measurement was also inaccurate in the cases of very heavy peening of the medium strength steel, since the rough peened surface offered a poor reference plane for the fairly shallow depths of damage. Figure 19 shows the relation of endurance limit to depth ratio for the 190,000 psi steel. Although the number of test points is limited, it appears that a depth ratio of about five represents the maximum improvement.

It was not possible to analyze the depth ratio for the 260,000 psi steel as the damage depths were extremely small and only ten peened and damaged specimens were tested. Nevertheless, this material, in the peened and damaged condition, showed about a 50% increase in endurance limit over the parent material and about a 110% increase over the unpeened damaged condition, as depicted in Figure 18.

In this regard it may be observed that endurance limits for the parent materials in the polished condition appear somewhat low. This may be a result of inclusions (which were observed in some failures) or of the polishing procedure. Polishing was done by hand, using decreasing sizes of grit and finishing with 600 grit abrasive paper. Although the polishing was performed with considerable care, differences in average endurance limit can be noted between groups of specimens of the same treatment but prepared at different times. These groups can be distinguished in Table 3 by discontinuity in numbering for specimens of the same treatment. Low values of

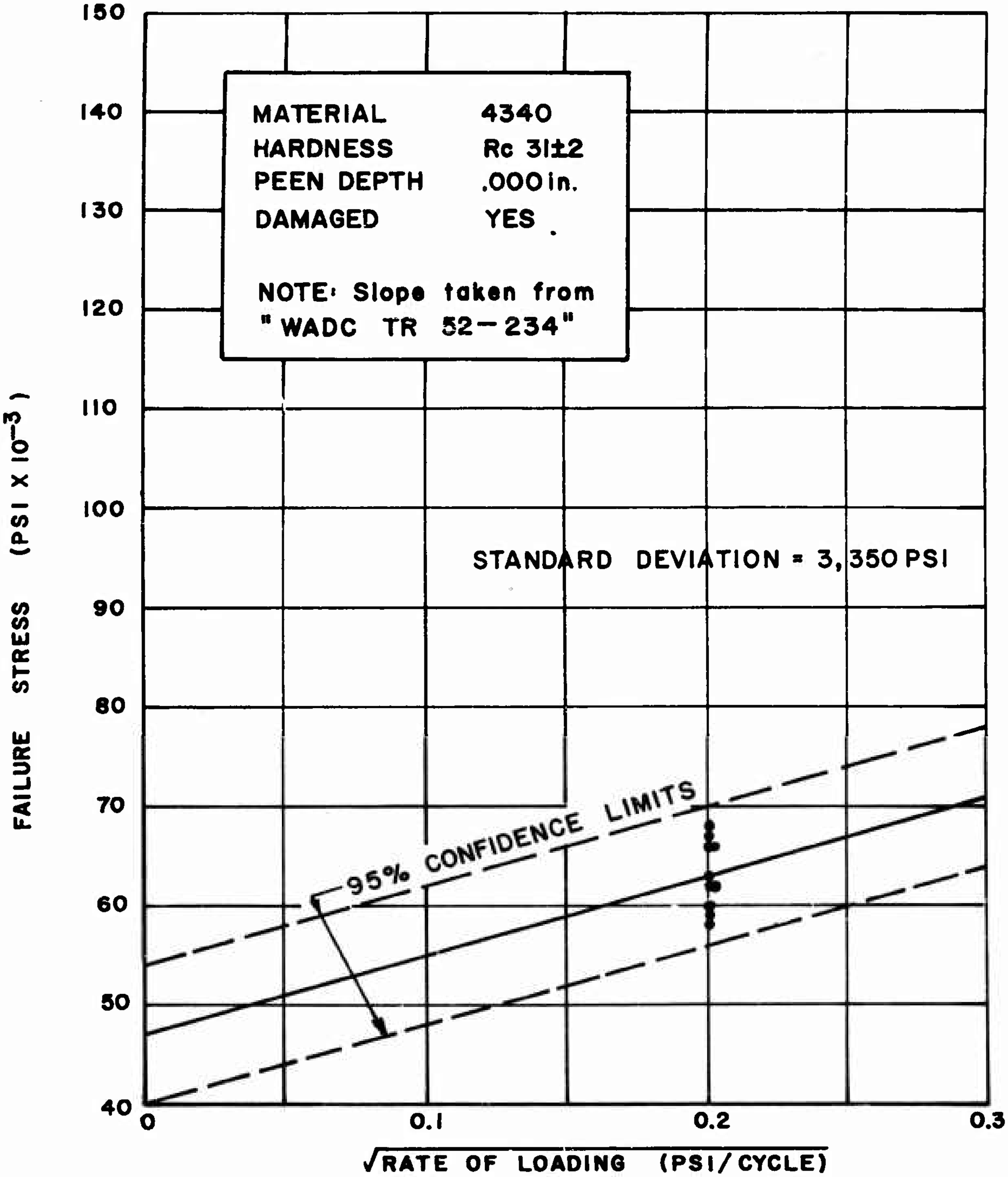

FIGURE 4. FATIGUE TEST RESULTS, Rc 31, .000 in. PEEN DEPTH, DAMAGED.

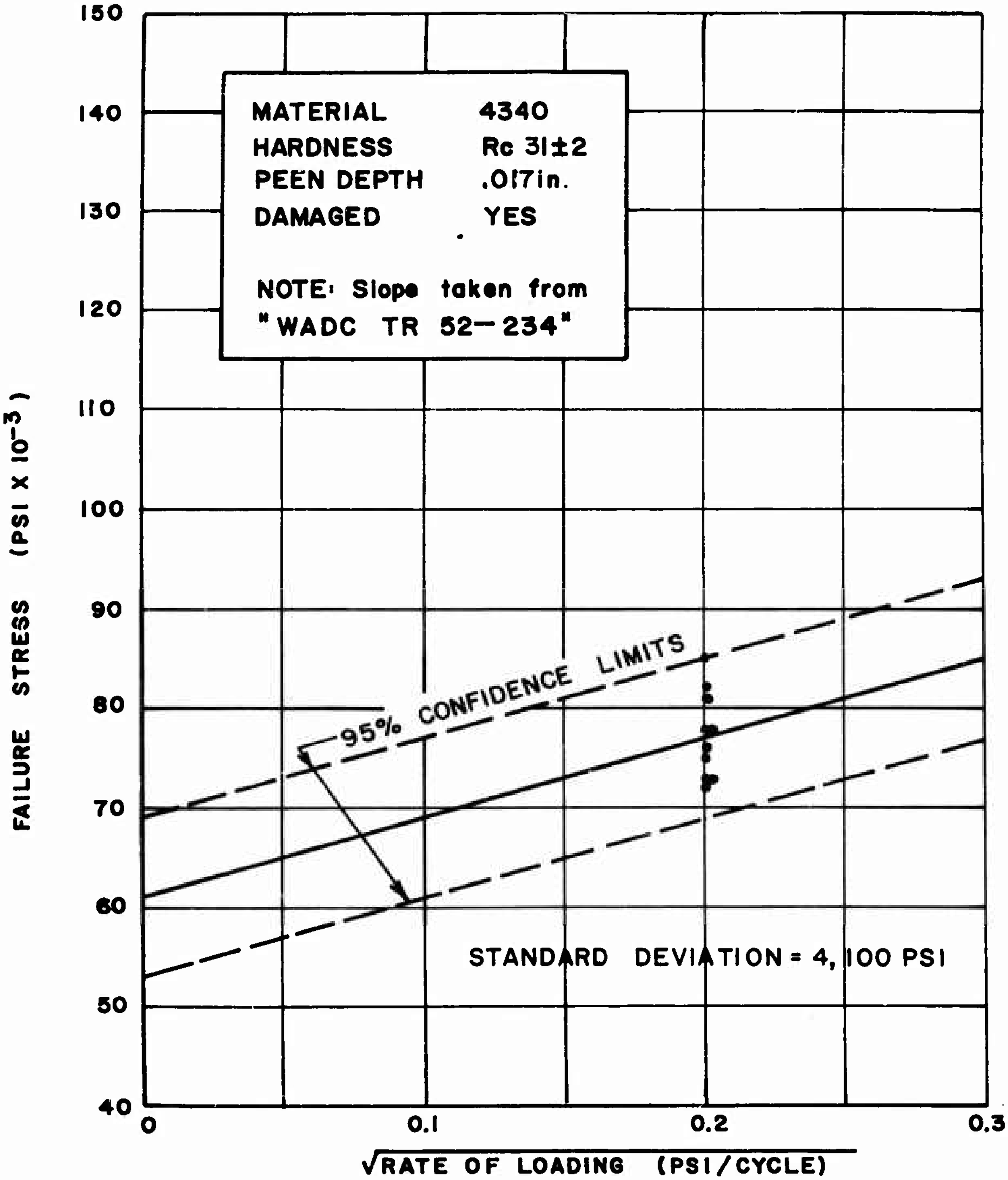

FIGURE 5. FATIGUE TEST RESULTS, Rc 31, .017 in. PEEN DEPTH, DAMAGED.

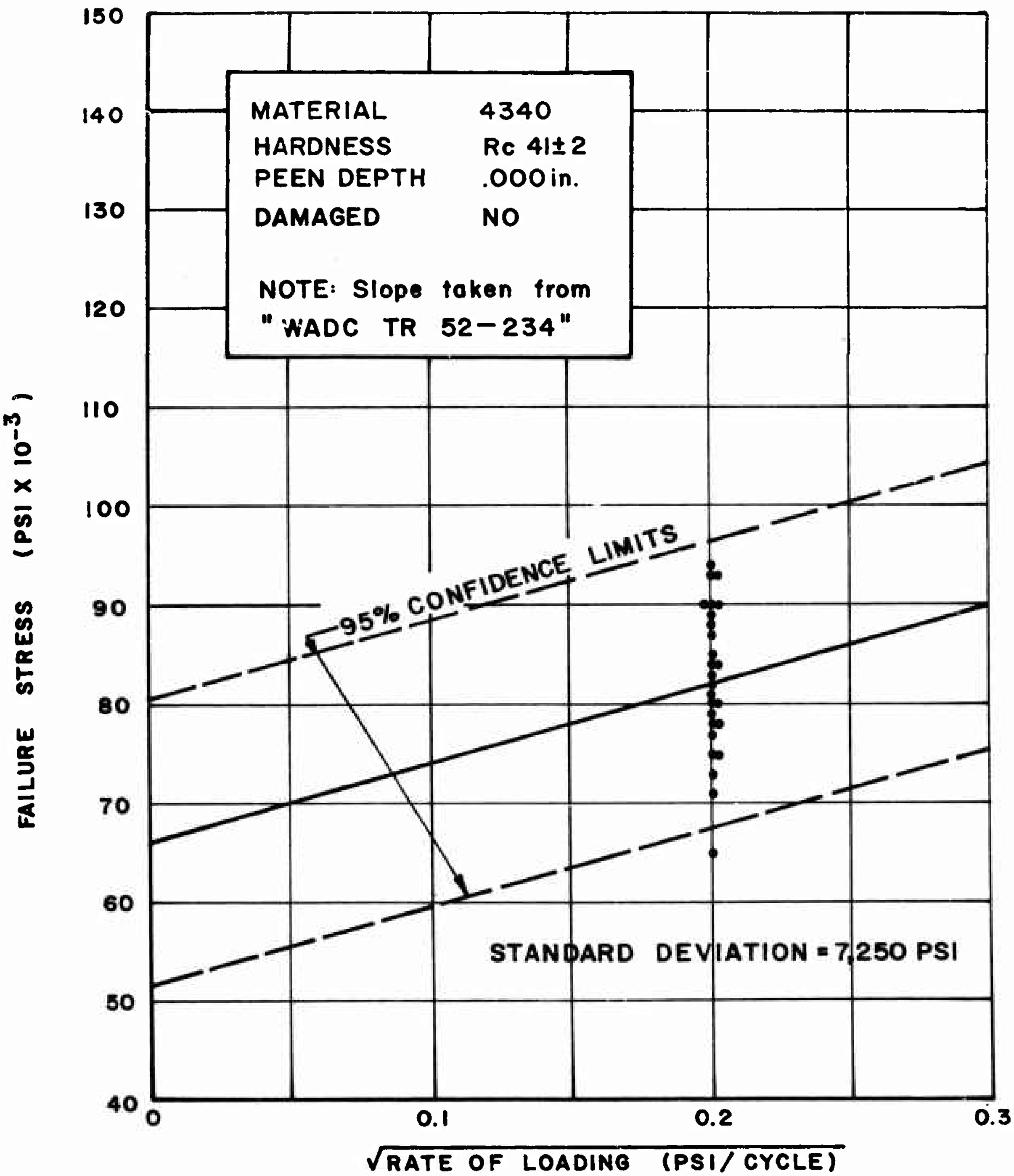

FIGURE 6. FATIGUE TEST RESULTS, Rc 41, .000 in. PEEN DEPTH, NO DAMAGE.

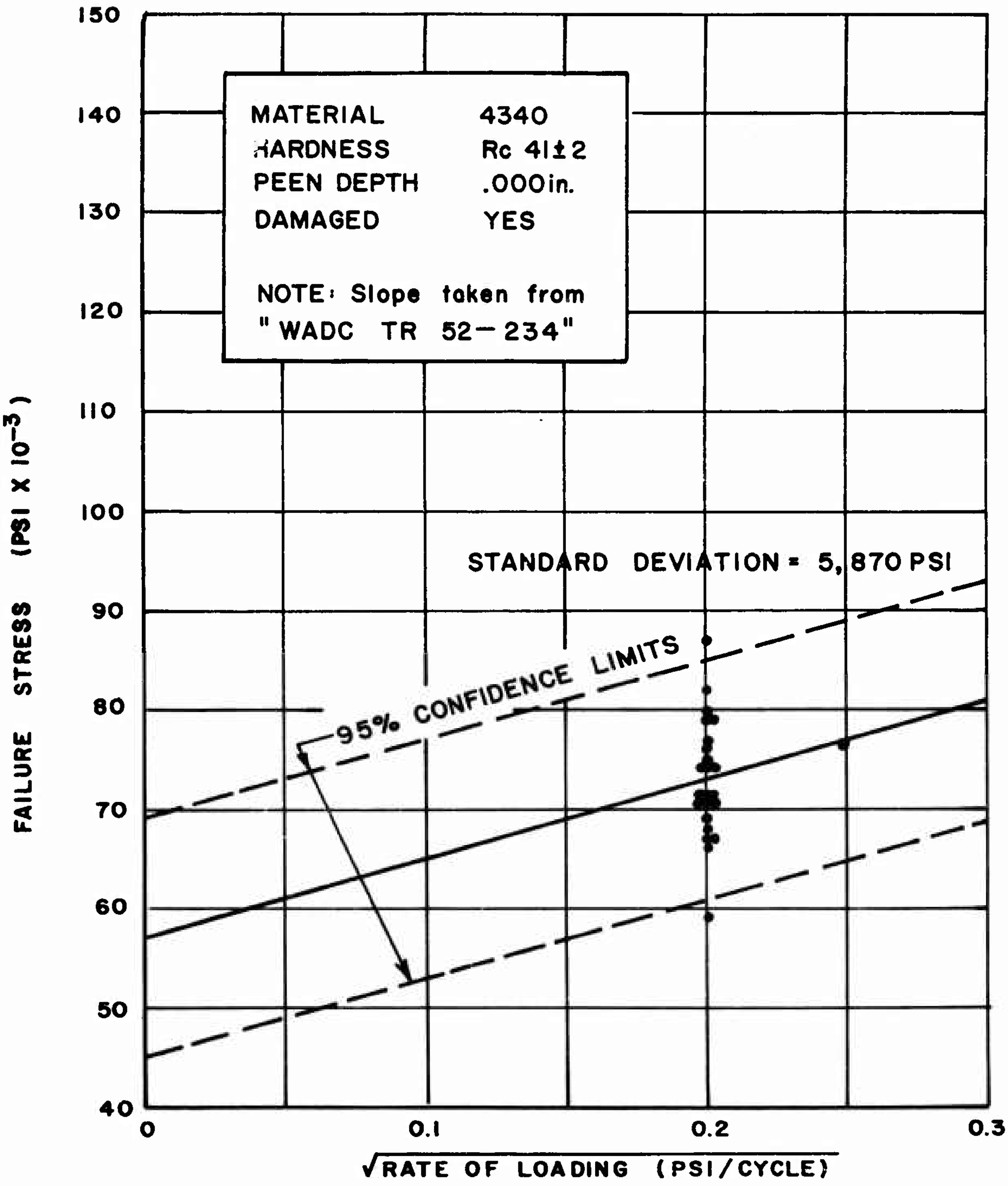

FIGURE 7. FATIGUE TEST RESULTS, Rc 41, .000 in. PEEN DEPTH, DAMAGED.

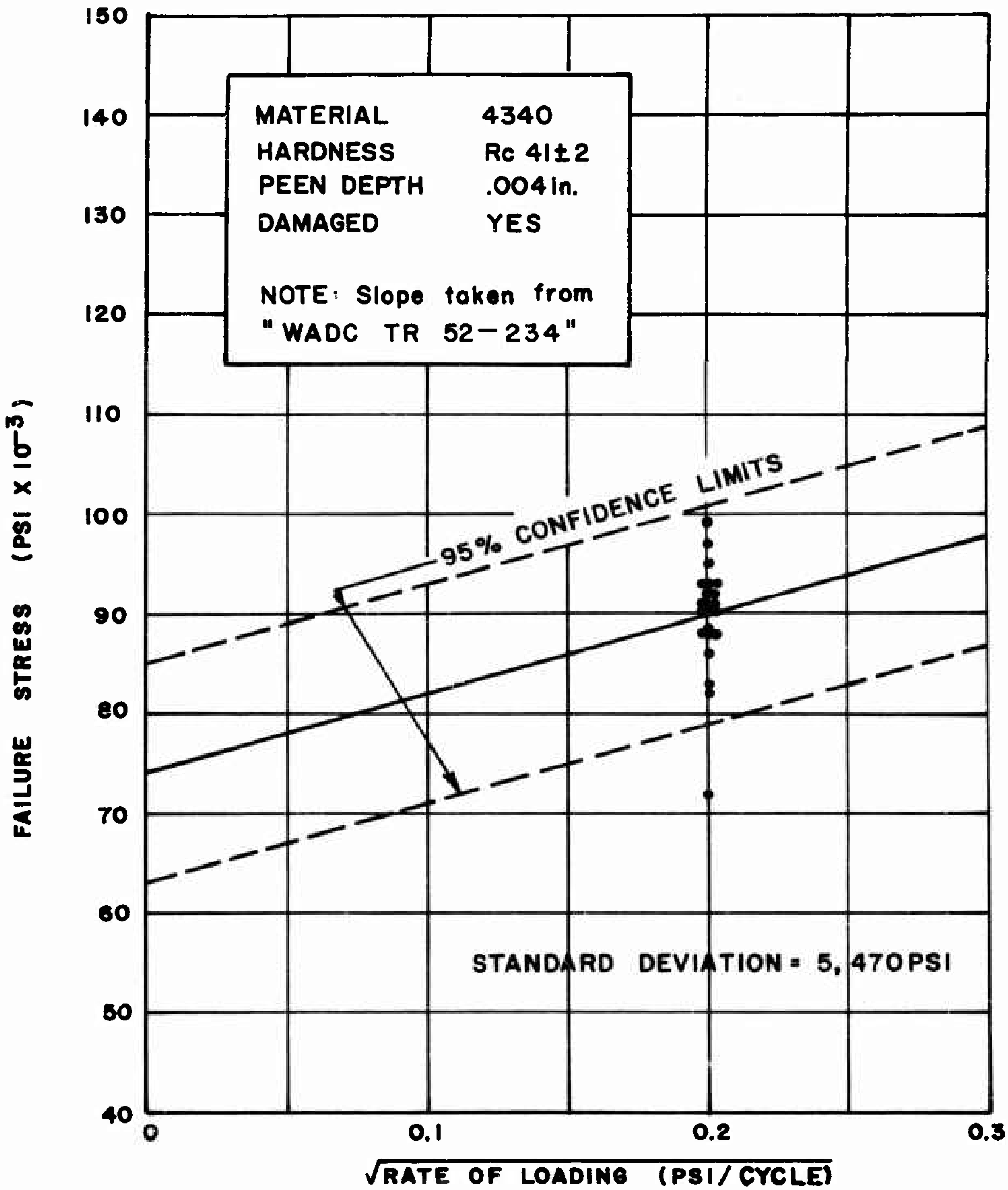

FIGURE 8. FATIGUE TEST RESULTS, Rc 41, .004 in. PEEN DEPTH, DAMAGED.

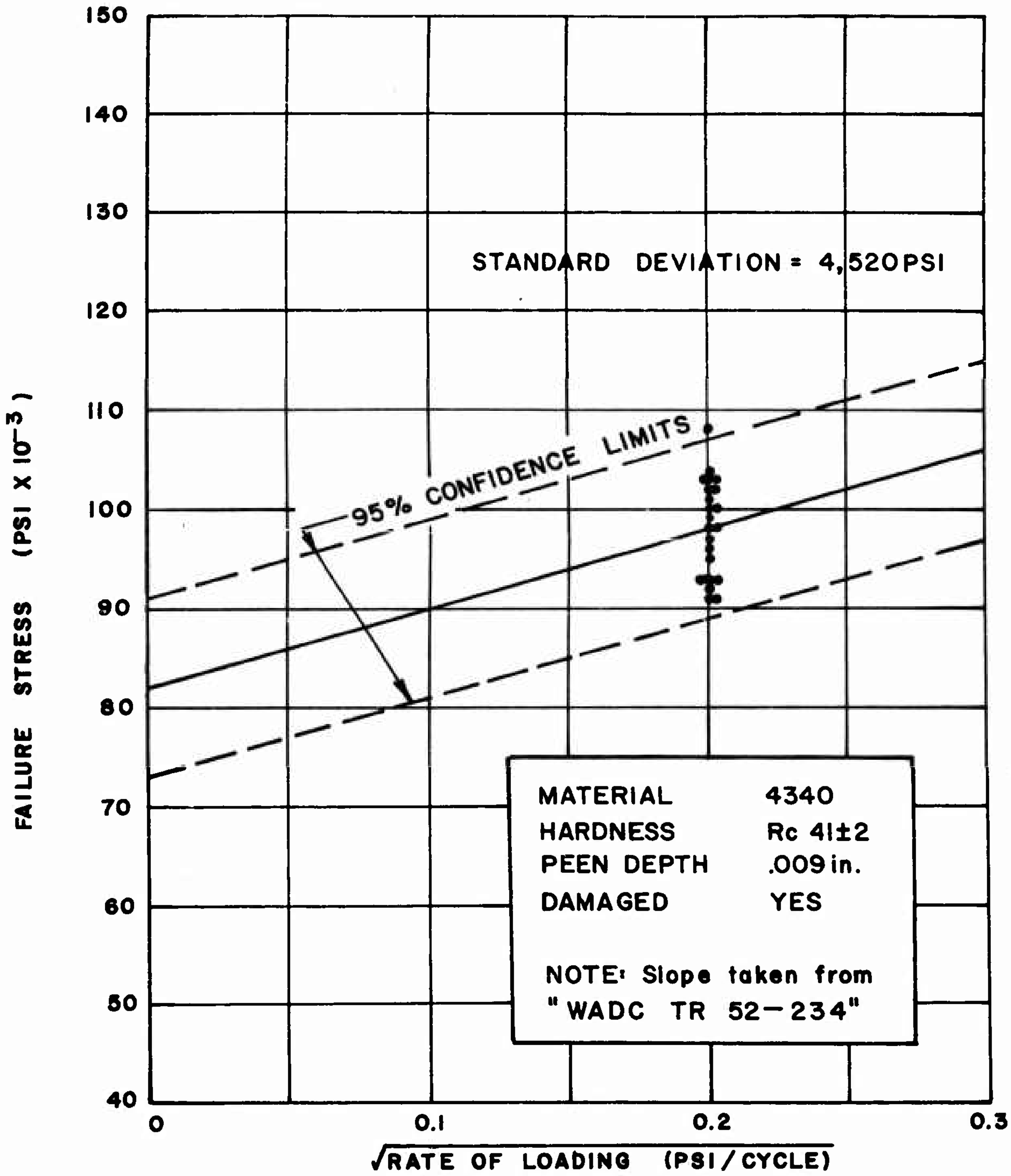

FIGURE 9. FATIGUE TEST RESULTS, Rc 41, .009 in. PEEN DEPTH, DAMAGED.

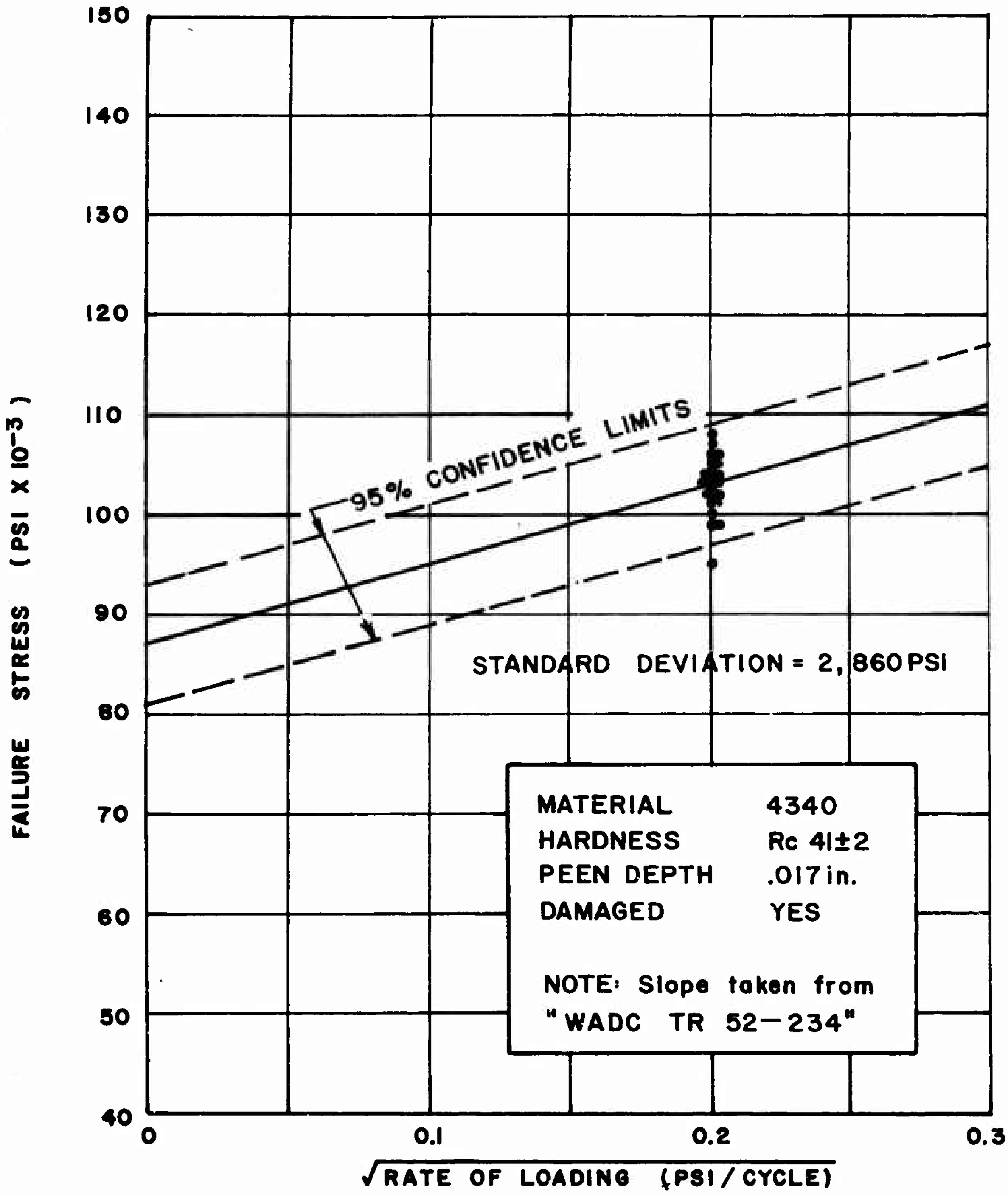

FIGURE 10. FATIGUE TEST RESULTS, Rc 41, .017 in. PEEN DEPTH, DAMAGED.

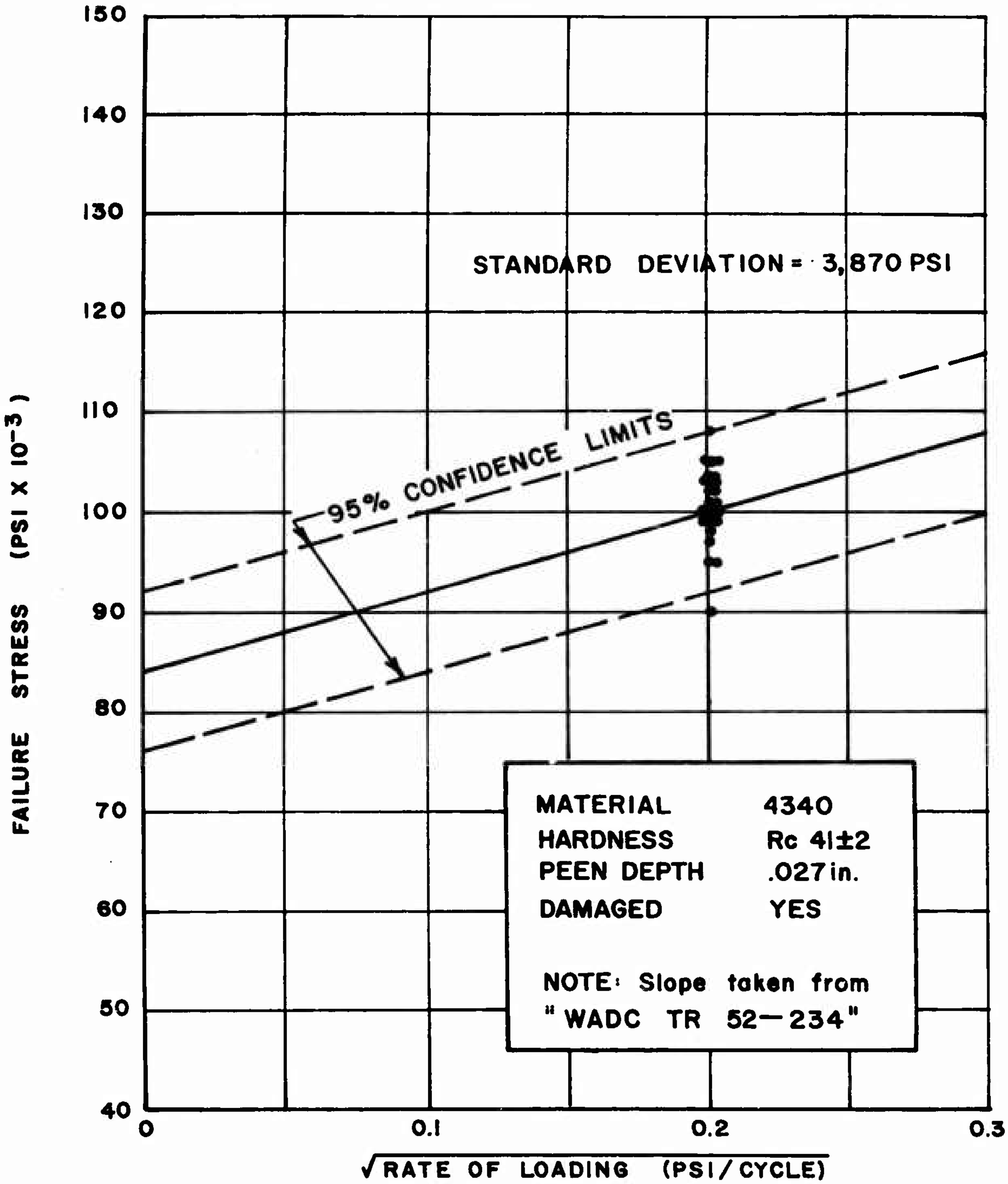

FIGURE 11. FATIGUE TEST RESULTS, Rc 41, .027 in. PEEN DEPTH, DAMAGED.

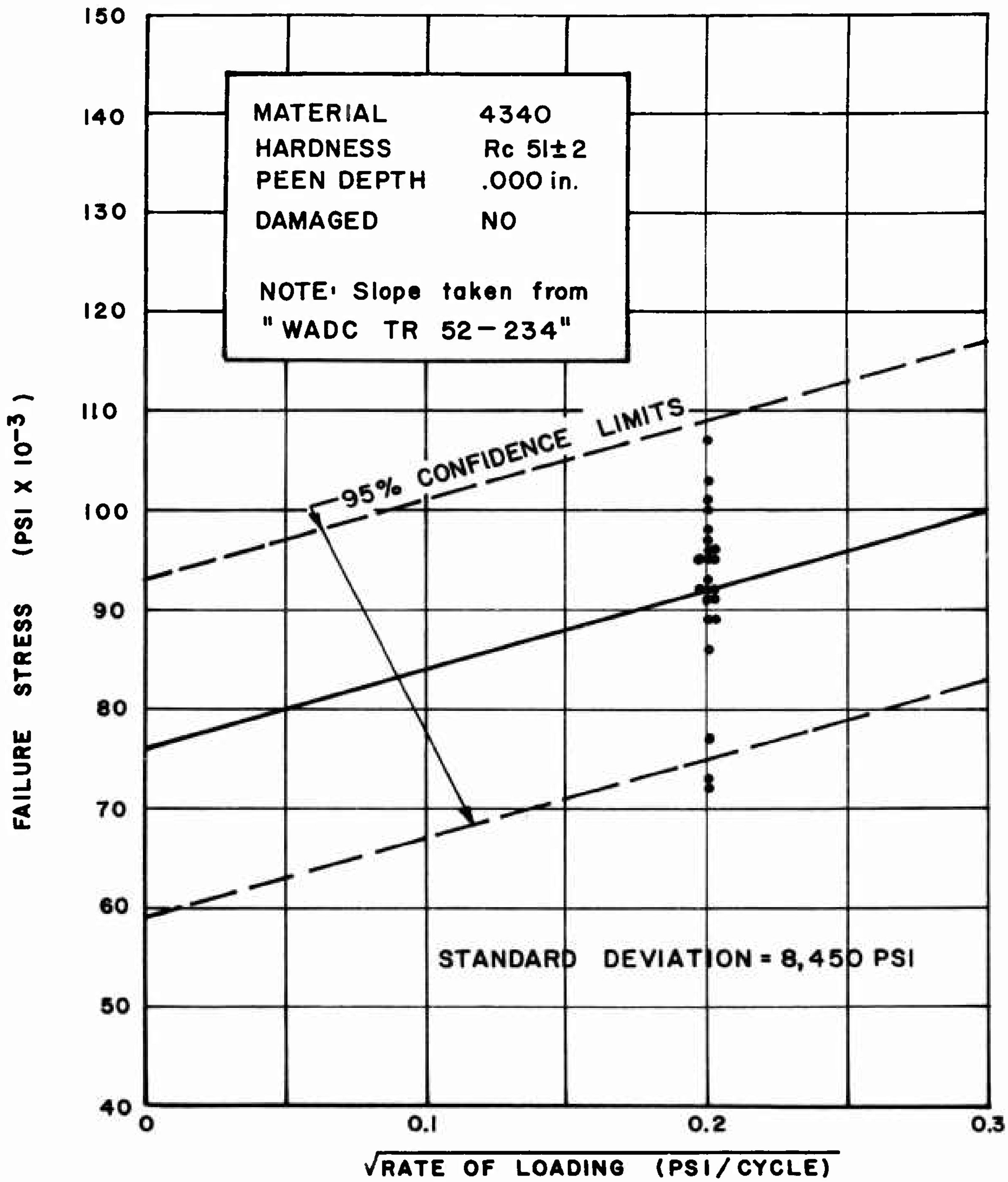

FIGURE 12. FATIGUE TEST RESULTS, Rc 51, .000 in. PEEN DEPTH, NO DAMAGE.

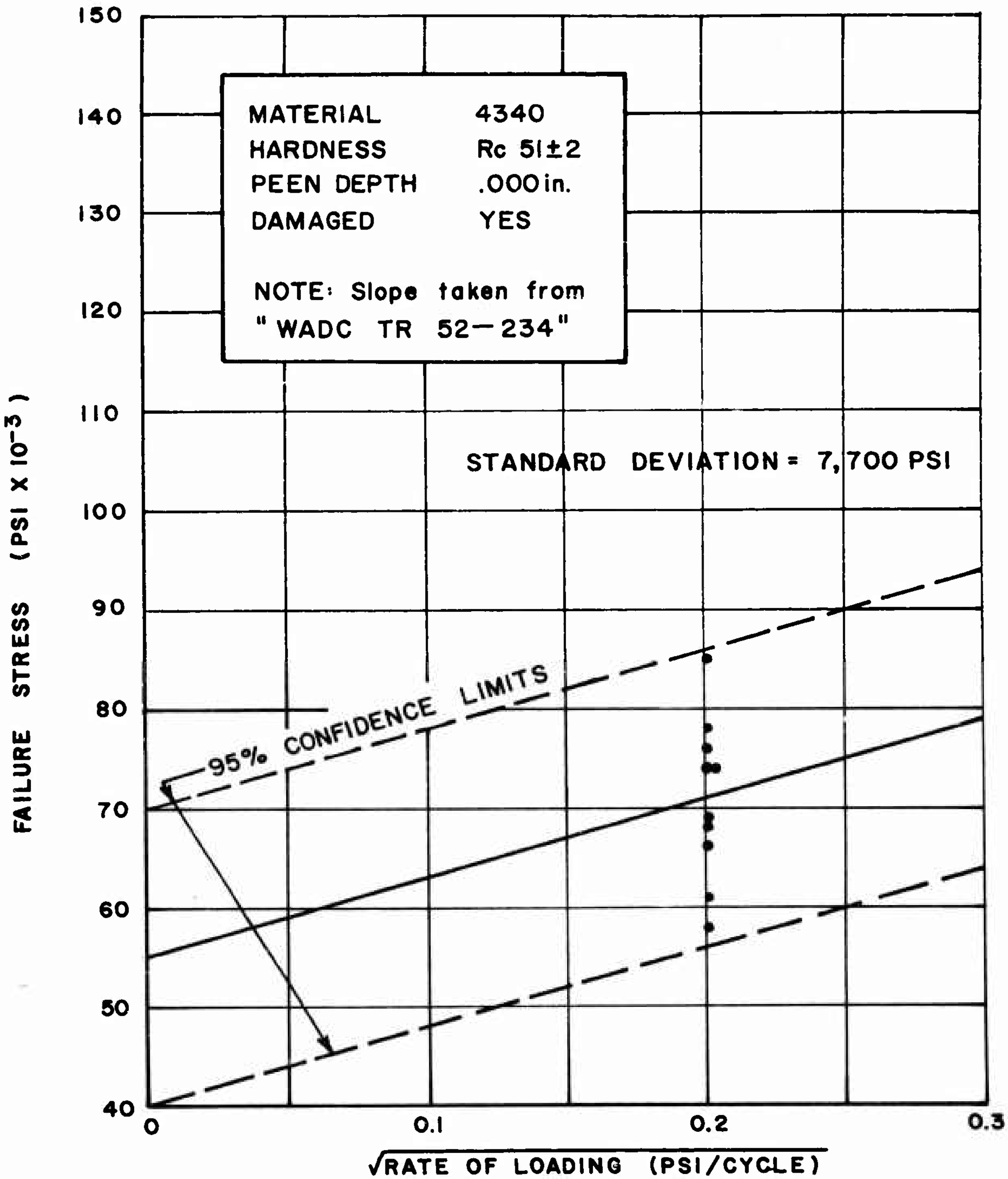

FIGURE 13. FATIGUE TEST RESULTS, Rc 51, .000 In. PEEN DEPTH, DAMAGED.

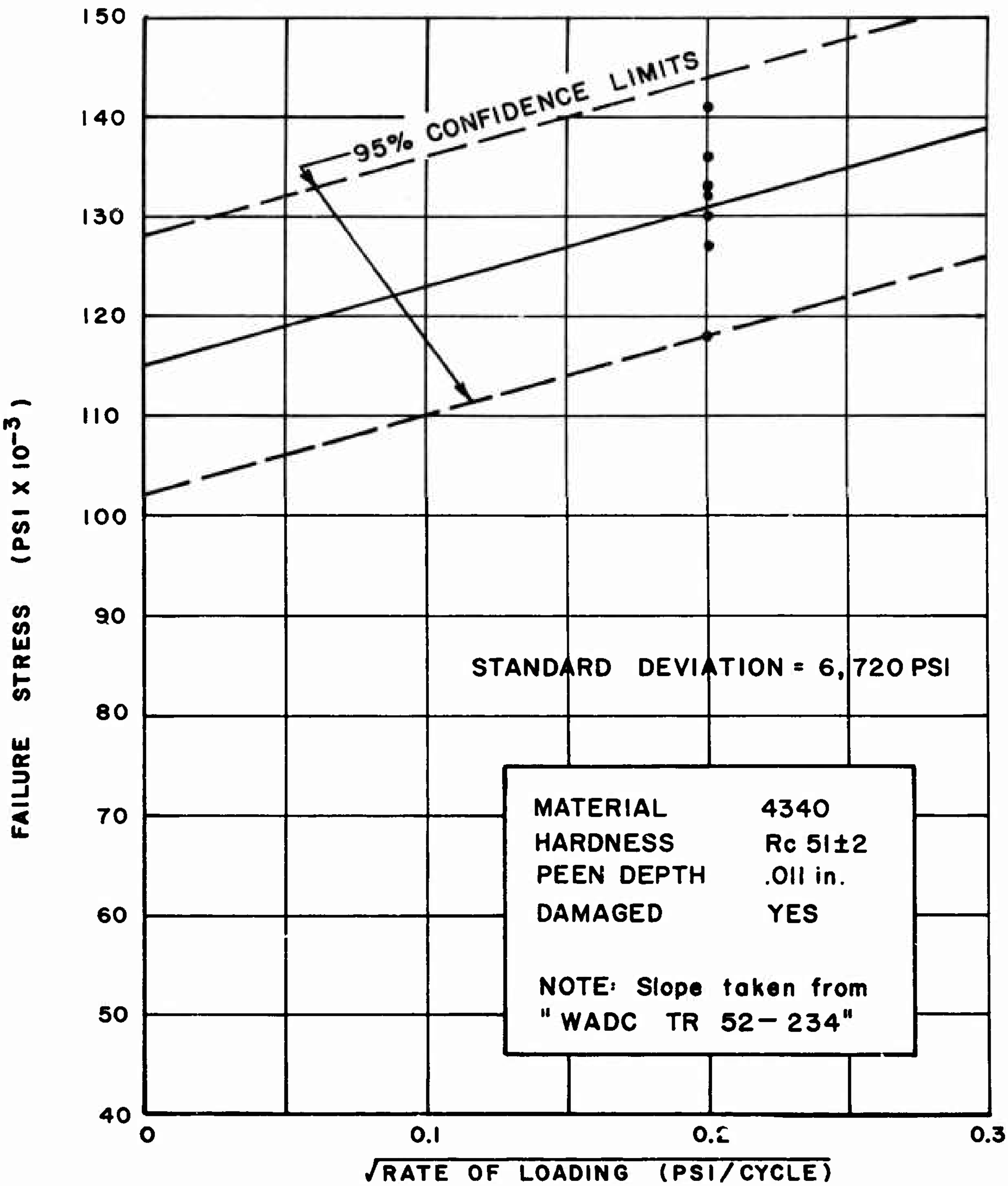

FIGURE 14. FATIGUE TEST RESULTS, Rc 51, .011 in. PEEN DEPTH, DAMAGED.

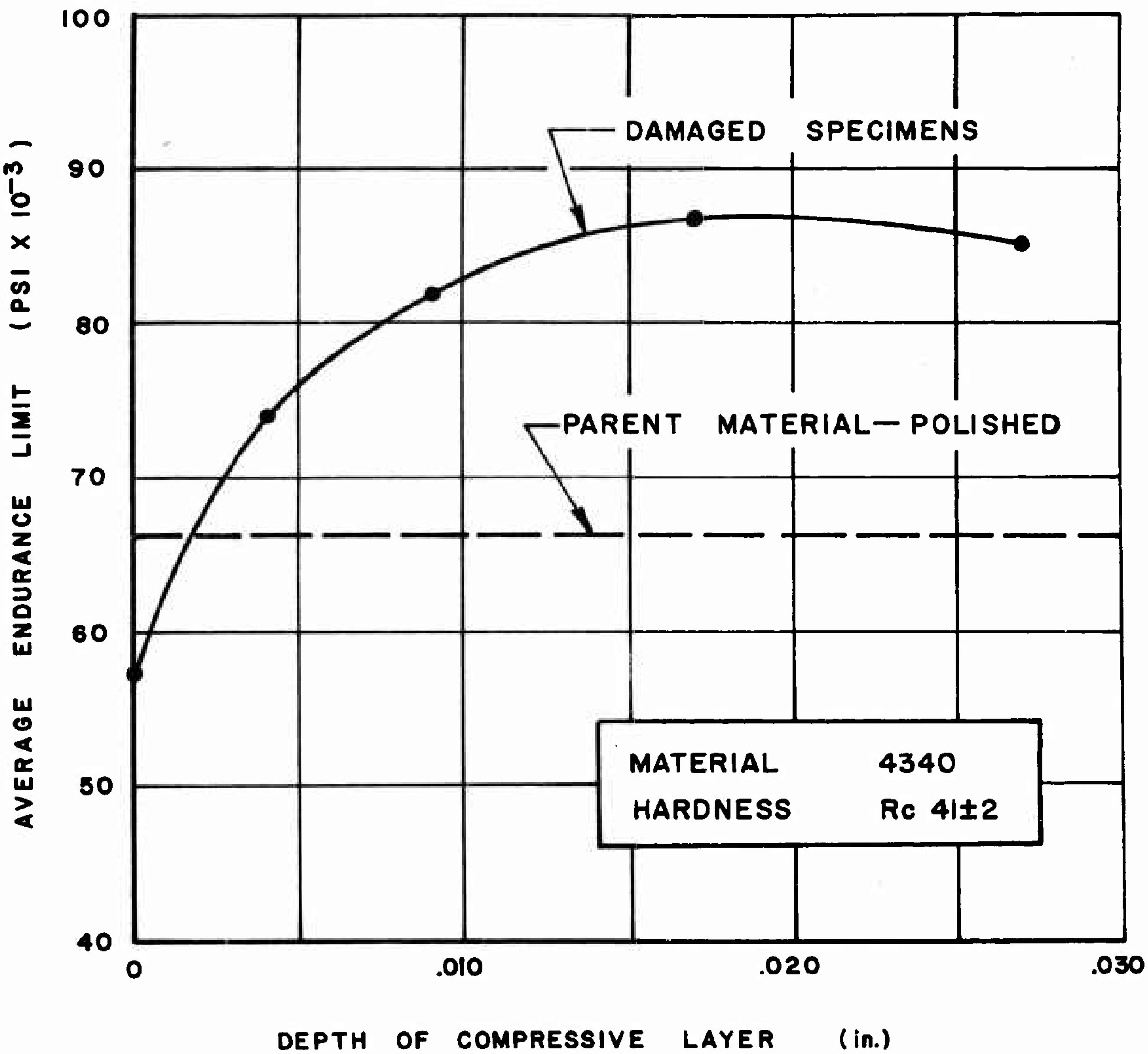

FIGURE 15. SUMMARY OF RESULTS — Rc 41

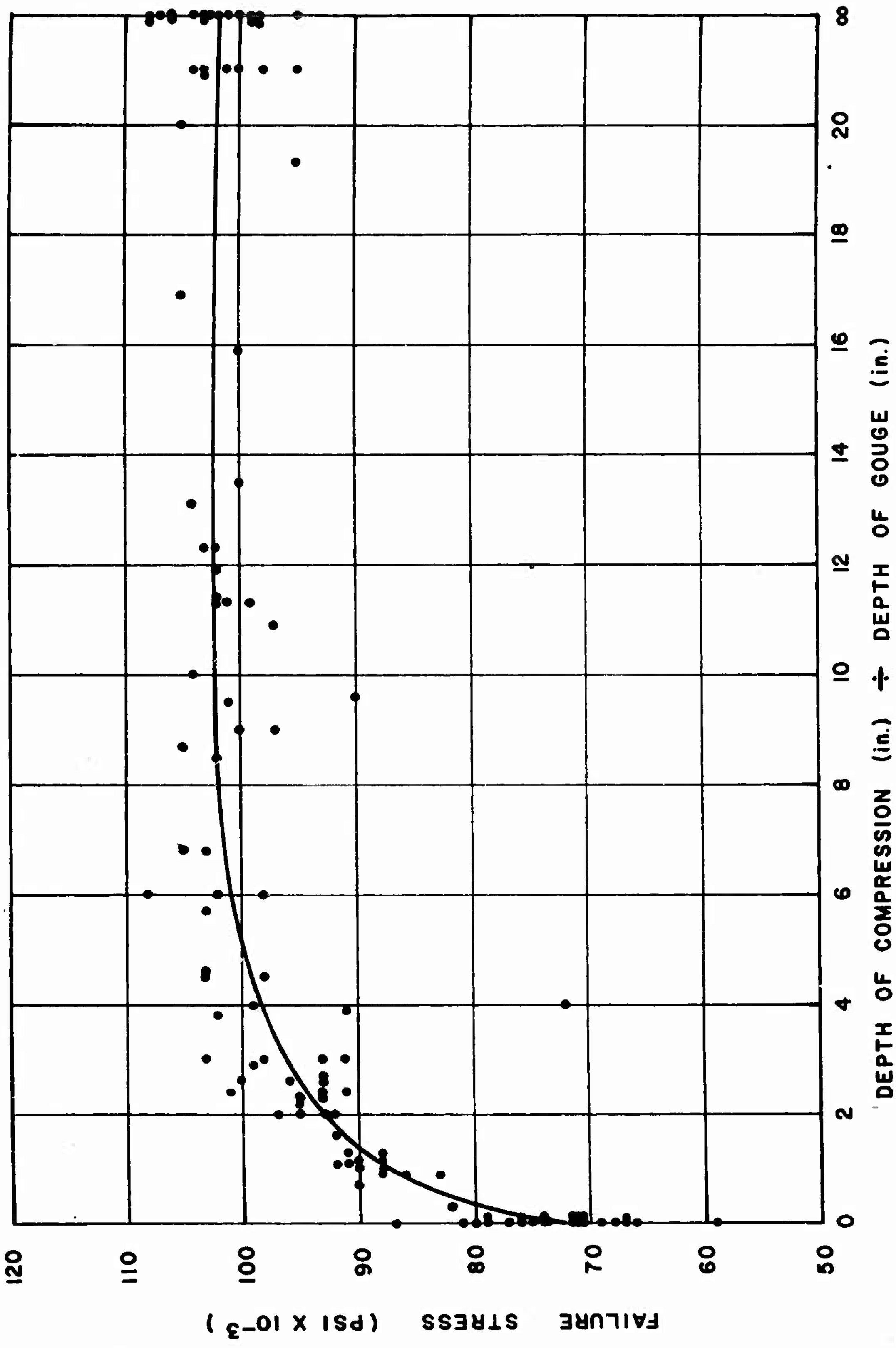

FIGURE 16. ENDURANCE LIMIT Vs. DEPTH RATIO OF Rc 41 DAMAGED SPECIMENS

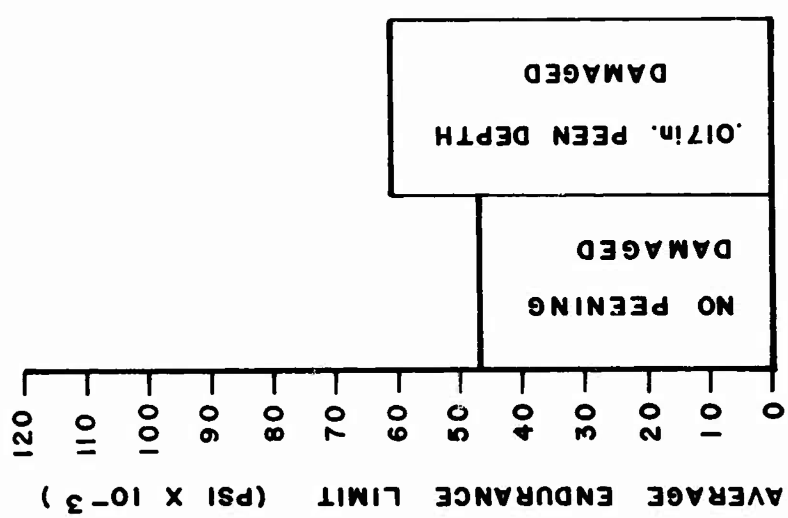

FIGURE 17. SUMMARY OF RESULTS—Rc 31

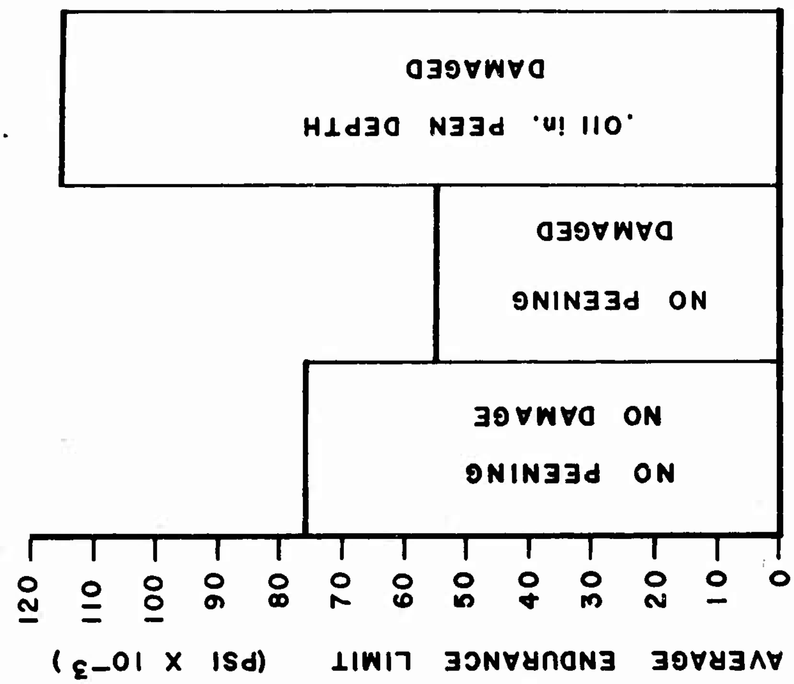

FIGURE 18. SUMMARY OF RESULTS—Rc 51

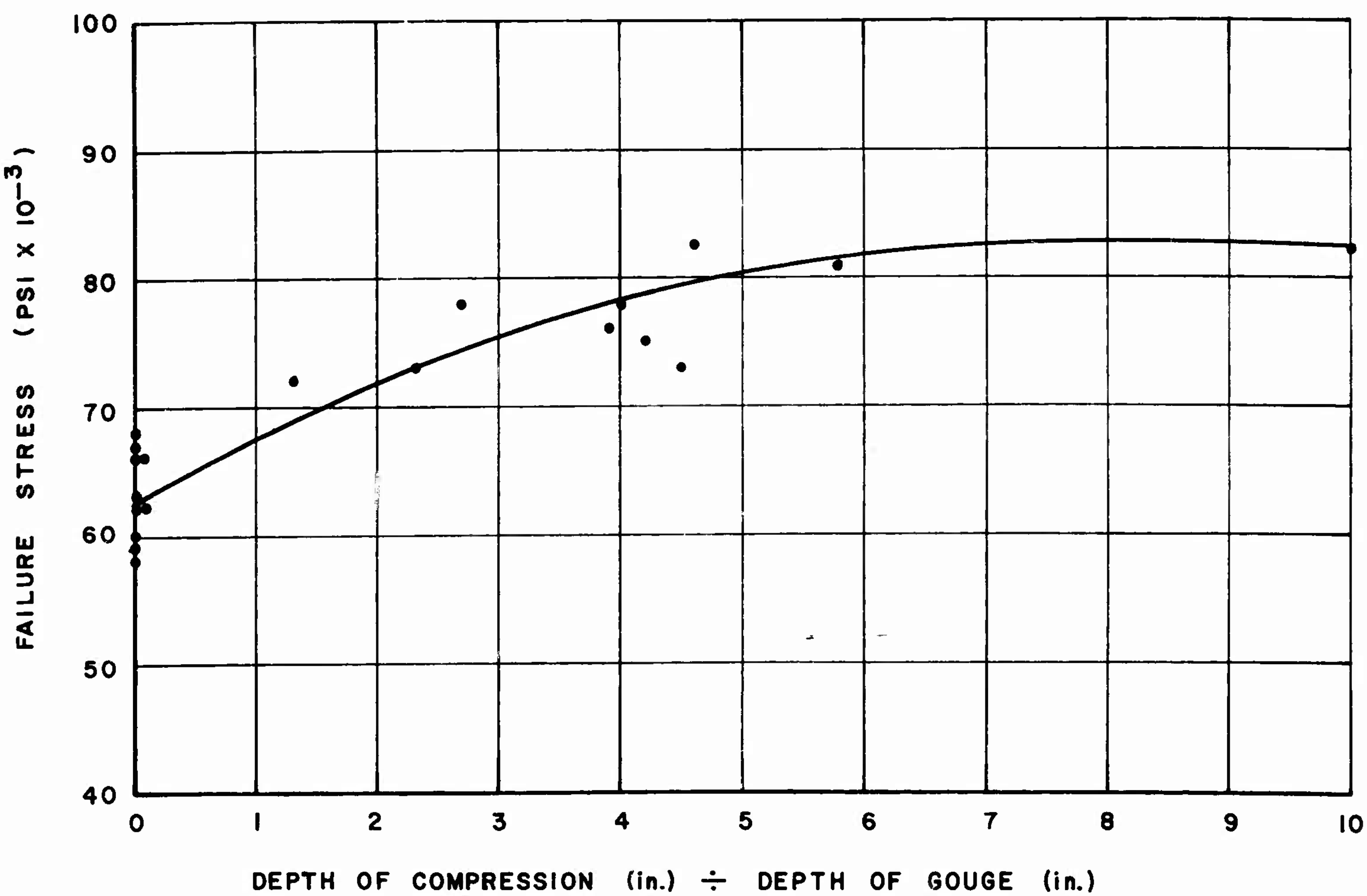

FIGURE 19. ENDURANCE LIMIT Vs. DEPTH RATIO OF Rc 31 DAMAGED SPECIMENS

endurance limit for the parent material would, of course, tend to make the benefits of peening appear large. Nevertheless, there can be little doubt that these benefits are of considerable magnitude.

Figures 20 through 45 are photographs of failed test specimens, showing several typical failures. Many of the cracks run to at least one edge of the specimen. This is usually a result of crack growth from a nucleus nearer the midpoint of the specimen, although some cracks did start at the chamfered edge. The stress at this edge is calculated to be less than one percent greater (due to anticlastic curvature) than the stress along the center line of the bar. In cases where there was doubt as to the origin of failure, the bars were broken in two and examined for beach marks pointing to the origin. In a few cases, two or more cracks were formed.

An attempt to analyze the nature of the simulated damage and its relation to fatigue failure was unsuccessful, except for the factor of gouge depth. Shape and form of the individual damage loci were so widely variant (as they are in service propellers) as to make it impossible to group them into patterns for analysis. In general the deeper gouges resulted in lowest endurance limits (as can be seen in Figure 16), although there were many exceptions.

IV. CONCLUSIONS

In general, it can be concluded that previous shot peening, properly controlled, considerably improves fatigue strength of damaged surfaces. Maximum improvement appears to occur under conditions where the depth of compressive residual stress is about five times the depth of the gouges introduced for the type of damage used in these tests. For depth ratios of less than five the improvement is less, but is still appreciable.

Benefits were more marked with increasing hardness of steel. The peened and damaged steels of 130,000 psi, 190,000 psi and 260,000 psi ultimate strength showed maximum increases in endurance limit of about 30%, 87% and 110%, respectively, over the unpeened but damaged cases.

Scatter of results decreased with increasing endurance limit such that the peening treatments giving the greater benefits also gave decreased scatter.

No conclusions can be drawn at present regarding the nature of surface damage and its relation to failure.

Some limitations on the use of shot peening in minimizing the effects of damage can be anticipated. First, it will be necessary to produce residual stress patterns of sufficient depth and magnitude to provide the desired benefits. There is a minimum blade thickness below which this cannot be accomplished. Second, the dimensional changes resulting from peening must be kept within tolerances. Here again there is a blade thickness below which this condition cannot be satisfied.

These limitations become less severe with increasing hardness of material. In harder material the depth of damage, hence the required depth of peening, is less than in softer material. Since dimensional change due to peening is primarily a function of depth of peening, less dimensional change would be encountered in applying adequate protective peening to a hard material than to a soft one.

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APPENDIX I

LIST OF SPECIMEN TREATMENTS AND FAILURE STRESSES

Table 3 lists the fatigue test specimens in groups according to the treatments received. Specimen numbers are consecutive except where additional tests were added to a group during the conduct of the investigation. These latter specimens carry numbers over 200 but are otherwise identical to those carrying lower numbers in the same group.

Table 4 lists the shot peening conditions applied to each group of specimens, according to depth of compressive residual stress.

TABLE 3

FATIGUE TEST SPECIMENS

Specimen No.	(R_c) Hardness	Depth of Compression	Failure Stress (psi)	Failure Gouge Depth	Remarks
1	41.0	None	88,000	None	Polished Surface
2	40.0	None	93,000	None	Polished Surface
2A	41.0	None	93,000	None	Polished Surface
3	42.5	None	78,000	None	Polished Surface
3A	41.5	None	81,000	None	Polished Surface
4	40.5	None	90,000	None	Polished Surface
5	41.5	None	79,000	None	Polished Surface
6	41.0	None	89,000	None	Polished Surface
7	42.0	None	85,000	None	Polished Surface
8	41.0	None	90,000	None	Polished Surface
9	41.0	None	84,000	None	Polished Surface
10	42.0	None	94,000	None	Polished Surface
211	44.0	None	71,000	None	Polished Surface
212	44.0	None	75,000	None	Polished Surface
213	45.0	None	82,000	None	Polished Surface
214	45.0	None	75,000	None	Polished Surface
215	45.0	None	77,000	None	Polished Surface
216	45.0	None	82,000	None	Polished Surface
217	44.0	None	80,000	None	Polished Surface
218	44.0	None	65,000	None	Polished Surface
219	44.0	None	84,000	None	Polished Surface
220	43.0	None	80,000	None	Polished Surface
221	45.0	None	87,000	None	Polished Surface
222	45.0	None	90,000	None	Polished Surface
223	44.0	None	78,000	None	Polished Surface
224	43.0	None	73,000	None	Polished Surface

TABLE 3 (CONTINUED)

FATIGUE TEST SPECIMENS

Specimen No.	(R_c) Hardness	Depth of Compression	Failure Stress (psi)	Failure Gouge Depth	Remarks
11	43.0	None	71,000	.004	
12	44.0	None	80,000	.002	
13	44.0	None	77,000	**	
14	43.5	None	67,000	**	
15	43.5	None	74,000	.002	
16	43.5	None	71,000	**	
17	44.0	None	71,000	.003	
18	41.0	None	76,000	.002	
19	44.5	None	66,000	.001	
20	43.5	None	74,000	.002	
21	44.0	None	59,000	**	
22	43.5	None	69,000	**	
23	45.0	None	79,000	.002	
24	44.0	None	75,000	.002	
25	43.5	None	71,000	.004	
26	44.0	None	77,000	**	
27	44.0	None	67,000	**	
28	44.5	None	68,000	**	
29	44.5	None	71,000	.001	
30	45.0	None	71,000	.004	
31	40.0	None	74,000	.002	
32	41.0	None	79,000	.006	
33	41.0	None	82,000	**	
34	41.5	None	87,000	**	

** Did not fail through a gouge.

TABLE 3 (CONTINUED)

FATIGUE TEST SPECIMENS

Specimen No.	(R_c) Hardness	Depth of Compression	Failure Stress (psi)	Failure Gouge Depth	Remarks
35	43.5	.004	93,000	.002	
36	44.0	.004	88,000	.004	
37	43.5	.004	83,000	.004	
38	44.0	.004	90,000	.006	
39	43.0	.004	92,000	.002	
40	44.5	.004	90,000	.004	
41	43.5	.004	88,000	.004	
42	44.5	.004	88,000	.004	
43	44.0	.004	91,000	.004	
44	43.0	.004	—	.002	Bad Test
45	43.0	.004	92,000	.004	
46	42.0	.004	93,000	.002	
47	43.0	.004	82,000	.002	
48	42.0	.004	95,000	.002	
49	40.0	.004	93,000	.002	
50	40.5	.004	91,000	.002	
51	41.5	.004	99,000	.001	
52	42.0	.004	86,000	.005	
53	41.5	.004	59,000	**	Failed Outside of Shot Peening Section
54	44.0	.004	91,000	.003	
55	42.5	.004	90,000	.0C4	
56	42.5	.004	97,000	.002	
57	42.0	.004	72,000	.001	Large Inclusion
58	42.5	.004	88,000	.003	

** Did not fail through a gouge.

TABLE 3 (CONTINUED)

FATIGUE TEST SPECIMENS

Specimen No.	(R_c) Hardness	Depth of Compression	Failure Stress (psi)	Failure Gouge Depth	Remarks
59	44.0	.009	101,000	.004	
60	43.5	.009	95,000	.004	
61	42.0	.009	103,000	.002	
62	42.5	.009	93,000	.004	
63	44.0	.009	93,000	.003	
64	43.0	.009	100,000	.001	
65	42.0	.009	96,000	.004	
66	41.5	.009	97,000	.001	
67	42.5	.009	98,000	.002	
68	41.5	.009	91,000	.002	
69	41.0	.009	—	.005	Bad Test
70	42.0	.009	—	.004	Bad Test
71	41.0	.009	108,000	.002	
72	43.0	.009	98,000	.003	
73	42.5	.009	93,000	.004	
74	42.5	.009	103,000	.002	
75	43.0	.009	100,000	.003	
76	43.5	.009	102,000	.002	
77	41.5	.009	92,000	.006	
78	41.0	.009	99,000	.003	
79	41.0	.009	102,000	.002	
80	42.0	.009	103,000	.003	
81	42.0	.009	91,000	.003	
82	43.0	.009	98,000	.002	

TABLE 3 (CONTINUED)

FATIGUE TEST SPECIMENS

Specimen No.	(R_c) Hardness	Depth of Compression	Failure Stress (psi)	Failure Gouge Depth	Remarks
83	41.0	.017	102,000	.002	
84	43.0	.017	104,000	.001	
85	43.0	.017	95,000	.008	
86	40.5	.017	102,000	**	
87	41.0	.017	—	**	Bad Test
88	41.0	.017	99,000	.002	
89	42.0	.017	102,000	.002	
90	42.0	.017	99,000	**	
91	42.5	.017	102,000	.002	
92	41.0	.017	104,000	**	
93	42.0	.017	107,000	**	
94	42.0	.017	103,000	.003	
95	40.5	.017	104,000	.002	
96	40.5	.017	100,000	**	
97	40.0	.017	108,000	**	
98	41.5	.017	106,000	**	
99	42.5	.017	101,000	.002	
100	42.0	.017	103,000	.003	
101	40.0	.017	103,000	**	
102	42.5	.017	104,000	**	
103	41.0	.017	105,000	.003	
104	42.0	.017	106,000	**	
105	40.0	.017	101,000	.002	
106	42.0	.017	105,000	**	

** Did not fail through a gouge.

TABLE 3 (CONTINUED)

FATIGUE TEST SPECIMENS

Specimen No.	(R_c) Hardness	Depth of Compression	Failure Stress (psi)	Failure Gouge Depth	Remarks
107	43.0	.027	100,000	**	
108	41.0	.027	105,000	.002	
109	43.0	.027	108,000	**	
110	42.0	.027	101,000	**	
111	42.0	.027	99,000	**	
112	41.0	.027	97,000	.003	
113	42.5	.027	103,000	**	
114	43.0	.027	102,000	.002	
115	42.5	.027	105,000	.001	
116	43.0	.027	99,000	**	
117	39.5	.027	95,000	**	
118	41.0	.027	102,000	.002	
119	43.0	.027	103,000	.001	
120	40.5	.027	103,000	.002	
121	41.0	.027	103,000	**	
122	43.5	.027	90,000	.028	Probable Inclusion
123	43.5	.027	100,000	.002	
124	44.0	.027	95,000	.001	
125	43.5	.027	103,000	**	
126	43.5	.027	99,000	**	
127	43.0	.027	100,000	.002	
128	43.5	.027	95,000	.001	
129	43.0	.027	101,000	.001	
130	43.0	.027	98,000	.001	

** Did not fail through a gouge.

TABLE 3 (CONTINUED)

FATIGUE TEST SPECIMENS

Specimen No.	(R_c) Hardness	Depth of Compression	Failure Stress (psi)	Failure Gouge Depth	Remarks
131	30.5	None	66,000	.002	
132	29.5	None	58,000	.004	
133	30.0	None	62,000	**	
134	29.0	None	63,000	.002	
135	30.0	None	67,000	.003	
136	30.0	None	60,000	.010	
137	30.5	None	68,000	.002	
138	30.5	None	66,000	.002	
139	29.0	None	62,000	**	
140	29.5	None	59,000	.005	
141	30.5	.017	85,000	.004	
142	29.0	.017	72,000	.013	
143	30.5	.017	73,000	.004	
144	29.5	.017	73,000	.007	
145	29.0	.017	78,000	.006	
146	30.5	.017	75,000	.004	
147	30.0	.017	76,000	.004	
148	30.0	.017	78,000	.004	
149	29.5	.017	81,000	.003	
150	30.0	.017	82,000	.002	

** Did not fail through a gouge.

TABLE 3 (CONTINUED)

FATIGUE TEST SPECIMENS

Specimen No.	(R_c) Hardness	Depth of Compression	Failure Stress (psi)	Failure Gouge Depth	Remarks
151	51.0	None	76,000	**	
152	50.5	None	58,000	**	
153	51.0	None	74,000	.002	
154	51.5	None	78,000	.001	
155	52.0	None	74,000	**	
156	50.0	None	69,000	**	
157	51.0	None	66,000	**	
158	52.0	None	68,000	**	
159	52.0	None	85,000	.002	
160	51.0	None	61,000	**	
161	52.0	.011	124,000	—	Failed Outside of Shot-Peened Section
162	52.0	.011	121,000	—	
163	51.5	.011	92,000	—	
164	51.0	.011	118,000	**	
165	52.0	.011	133,000	**	
166	51.5	.011	136,000	**	
167	52.5	.011	130,000	**	
168	51.0	.011	141,000	**	
169	52.0	.011	127,000	**	
170	51.5	.011	132,000	.001	

** Did not fail through a gouge.

TABLE 3 (CONTINUED)

FATIGUE TEST SPECIMENS

Specimen No.	(R_c) Hardness	Depth of Compression	Failure Stress (psi)	Failure Gouge Depth	Remarks
231	54.0	None	100,000	None	Polished Surface
232	54.0	None	73,000	None	Polished Surface
233	53.0	None	92,000	None	Polished Surface
234	54.0	None	93,000	None	Polished Surface
235	54.0	None	72,000	None	Polished Surface
236	54.0	None	91,000	None	Polished Surface
237	54.0	None	89,000	None	Polished Surface
238	53.0	None	86,000	None	Polished Surface
239	54.0	None	98,000	None	Polished Surface
240	54.0	None	77,000	None	Polished Surface
241	55.0	None	91,000	None	Polished Surface
242	54.0	None	103,000	None	Polished Surface
243	54.0	None	96,000	None	Polished Surface
244	54.0	None	95,000	None	Polished Surface
245	54.0	None	97,000	None	Polished Surface
246	54.0	None	97,000	None	Polished Surface
247	54.0	None	101,000	None	Polished Surface
248	54.0	None	95,000	None	Polished Surface
249	54.0	None	107,000	None	Polished Surface
250	54.0	None	95,000	None	Polished Surface
251	54.0	None	92,000	None	Polished Surface
252	54.0	None	96,000	None	Polished Surface
253	54.0	None	89,000	None	Polished Surface
254	54.0	None	92,000	None	Polished Surface

TABLE 4

SHOT PEENING CONDITIONS

SAE 4340 Steel

Hardness (R_c)	Depth of Compression (in.)	Shot Diameter (in.)	Air Pressure (psig)
31	.017	.039	50
41	.004	.011	30
41	.009	.023	50
41	.017	.066	50
41	.027	.125	90
51	.011	.039	50

APPENDIX II

FAILED SPECIMENS

Figures 20 through 45 are included to show the general appearance of the shot peened surfaces, the artificial damage and the failures. The triangular pointer at the side of each photograph indicates the location of the failure. In case of multiple failures, multiple photographs are included. Photographs are approximately 4X magnification.

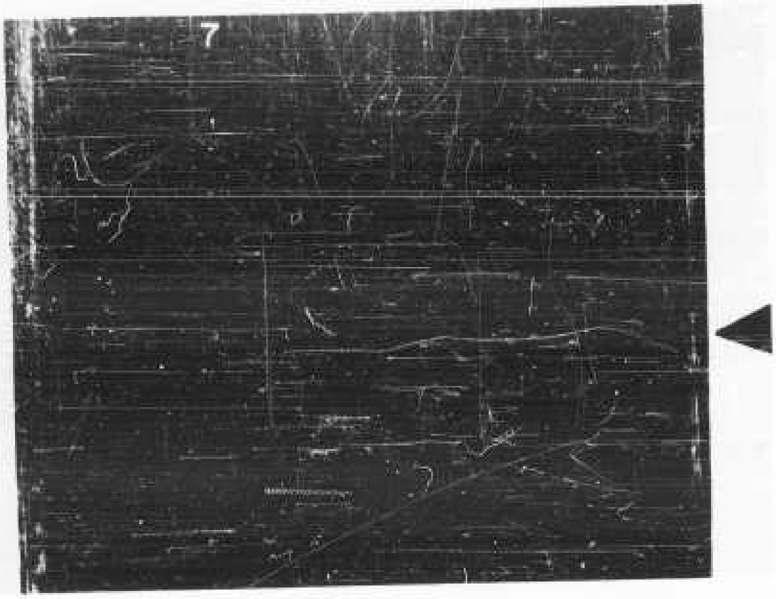

FIGURE 20. FAILURE IN SPECIMEN NO. 7

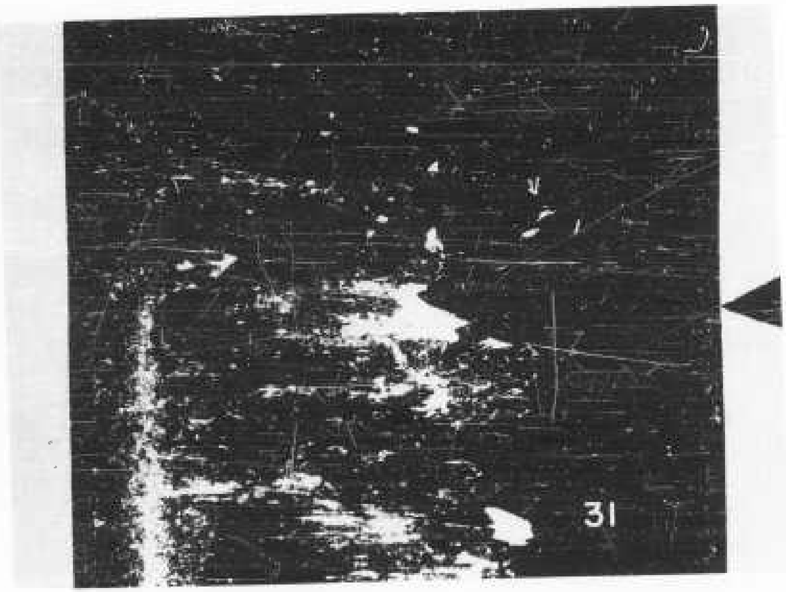

FIGURE 21. FAILURE IN SPECIMEN NO. 31

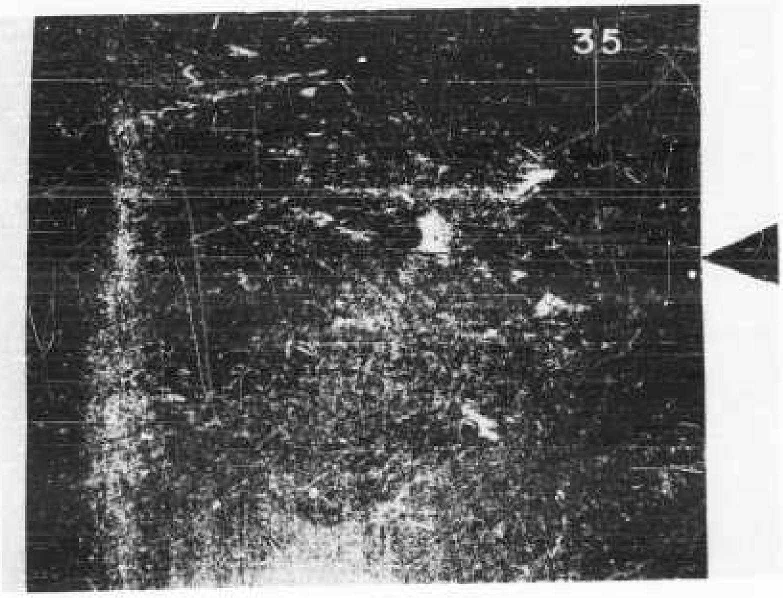

FIGURE 22. FAILURE IN SPECIMEN NO. 35

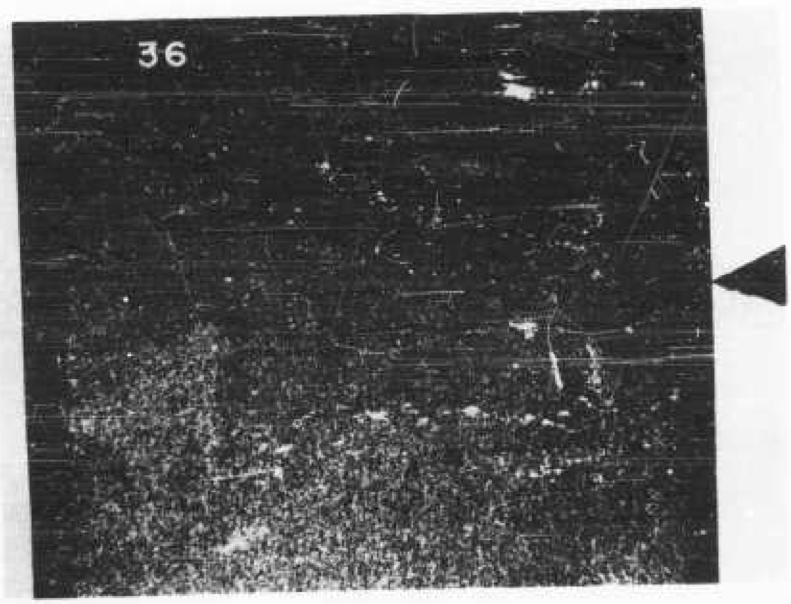

FIGURE 23. FAILURE IN SPECIMEN NO. 36

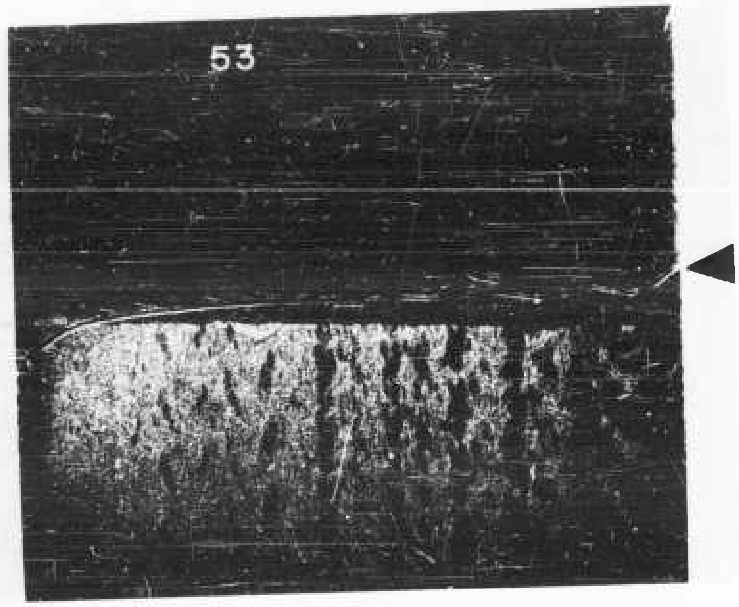

FIGURE 24. FAILURE IN SPECIMEN NO. 53

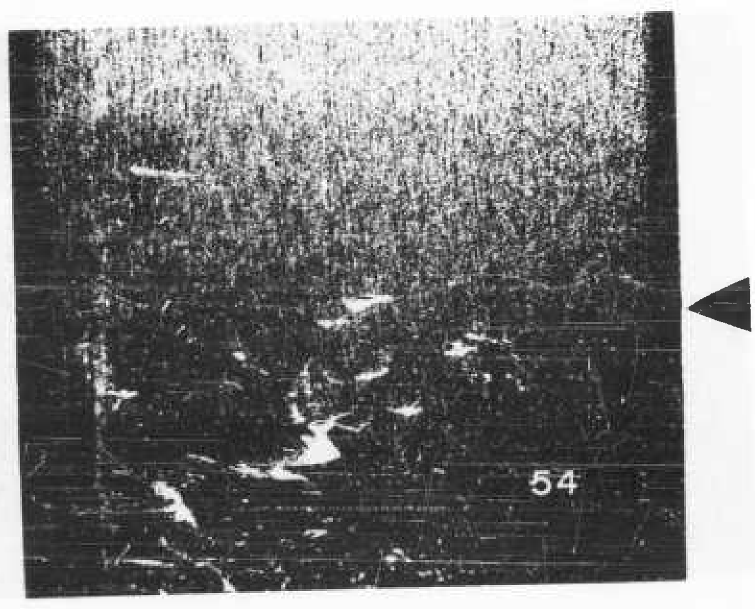

FIGURE 25. FAILURE IN SPECIMEN NO. 54

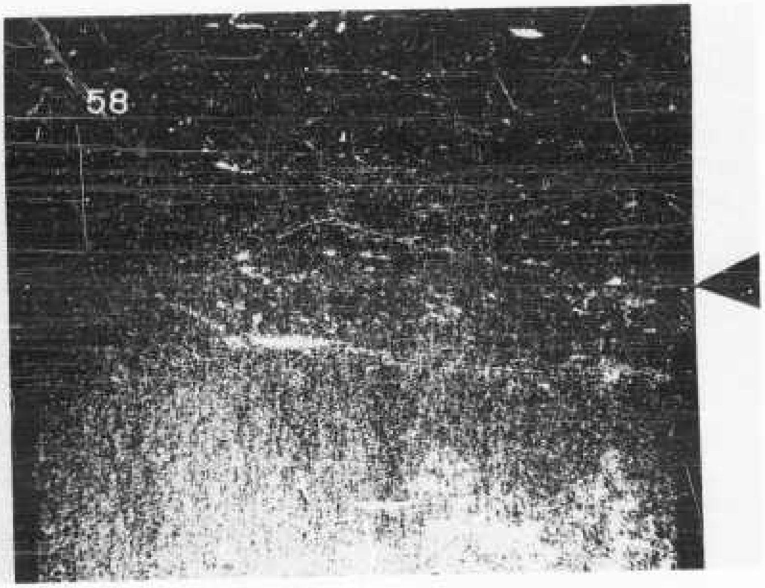

FIGURE 26. FAILURE IN SPECIMEN NO. 58

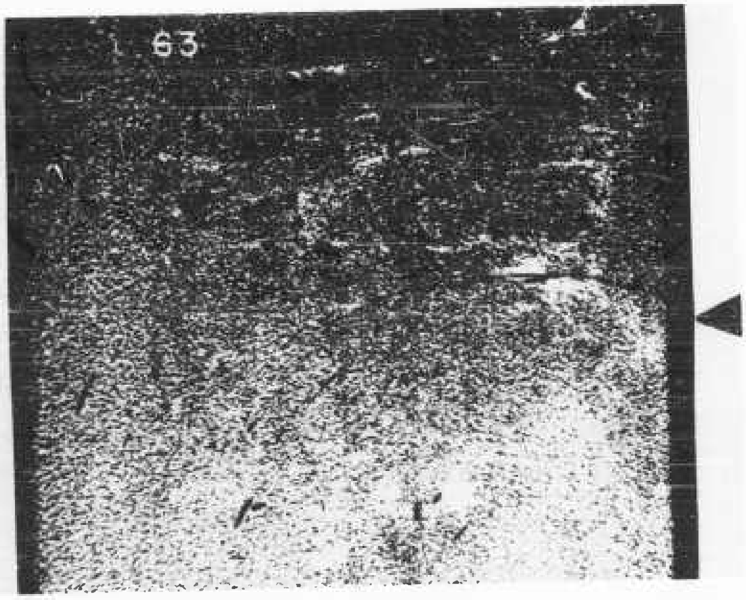

FIGURE 27. FAILURE IN SPECIMEN NO. 63.

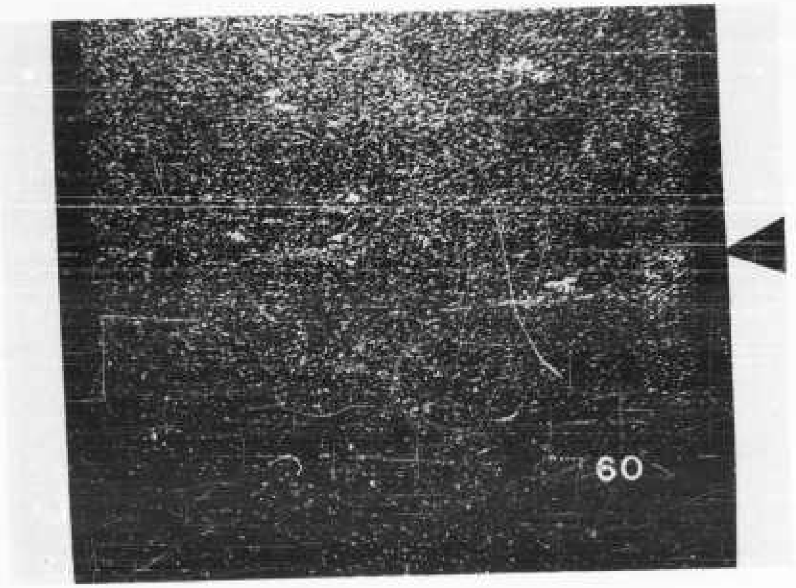

FIGURE 28. FAILURE IN SPECIMEN NO. 60

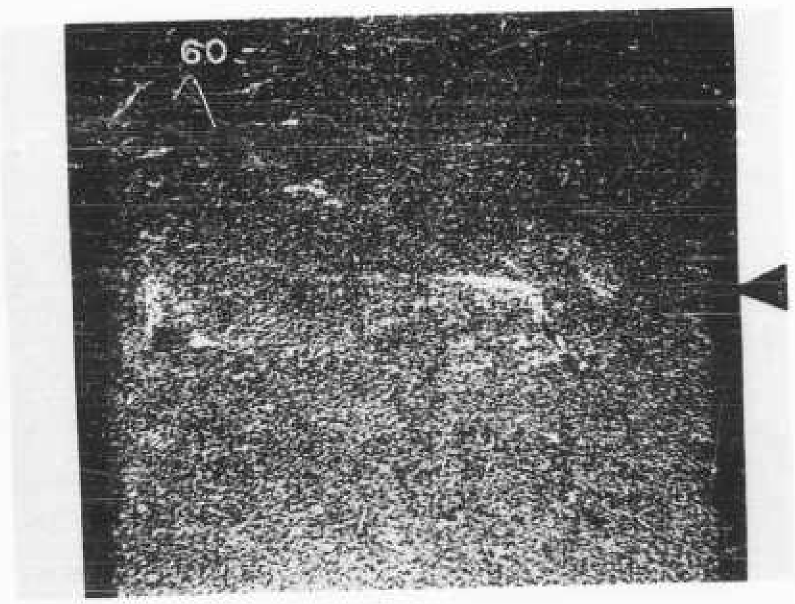

FIGURE 29. FAILURE IN SPECIMEN NO. 60

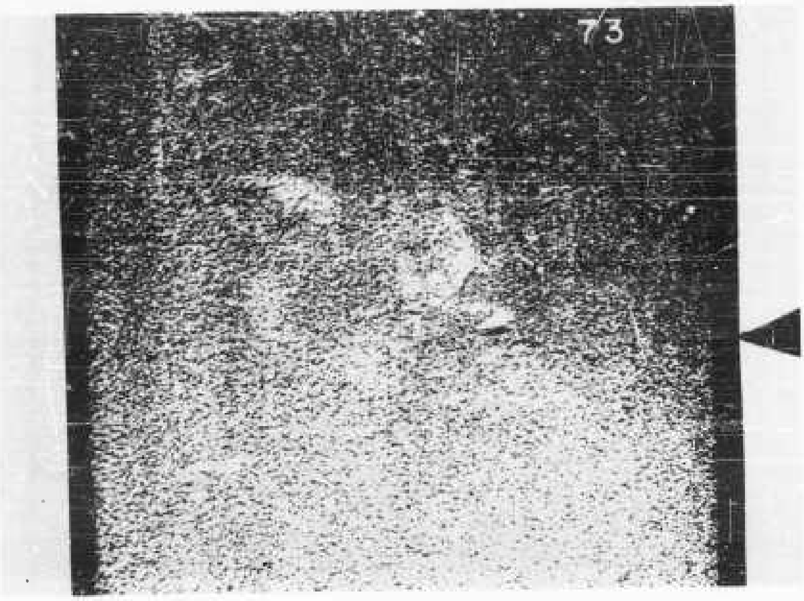

FIGURE 30. FAILURE IN SPECIMEN NO. 73

FIGURE 31. FAILURE IN SPECIMEN NO. 77

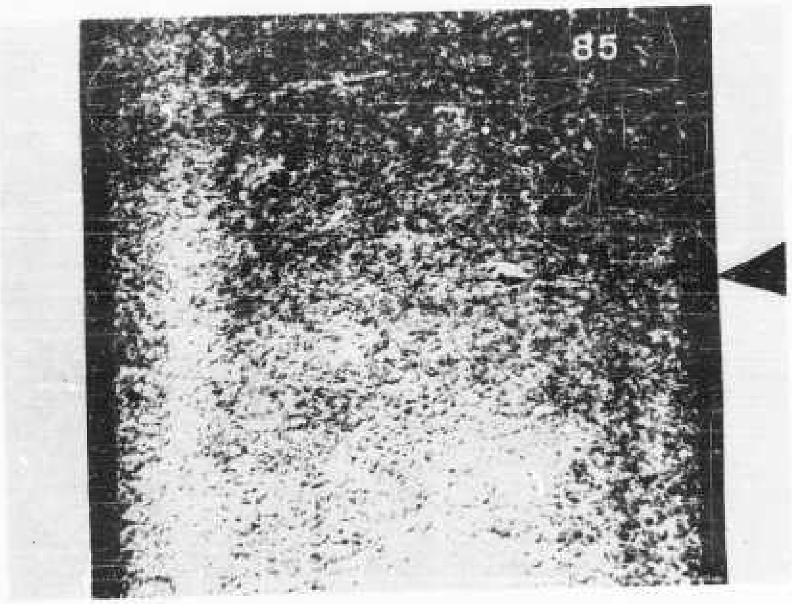

FIGURE 32. FAILURE IN SPECIMEN NO. 85

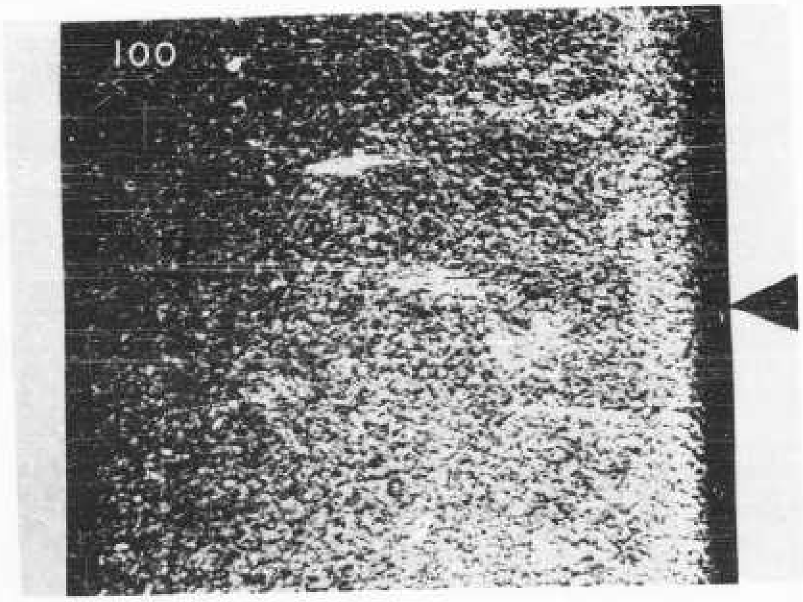

FIGURE 33. FAILURE IN SPECIMEN NO. 100

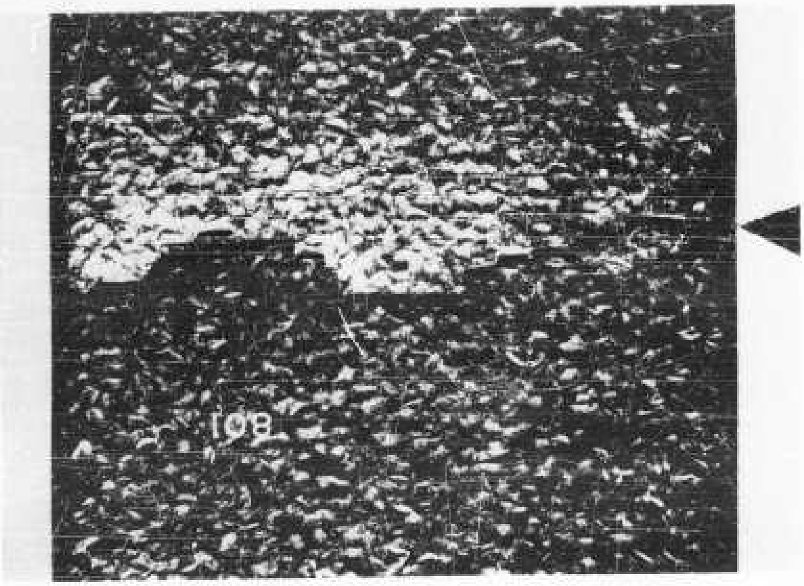

FIGURE 34. FAILURE IN SPECIMEN NO. 108

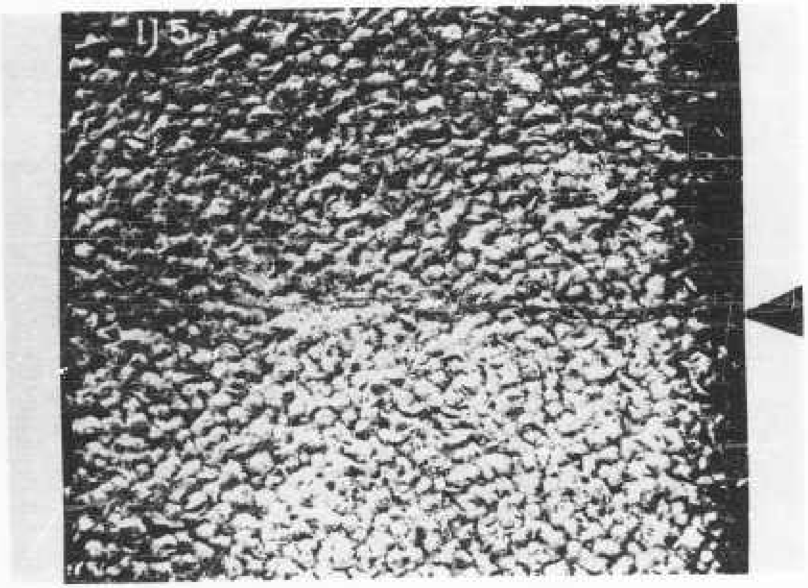

FIGURE 35. FAILURE IN SPECIMEN NO. 115

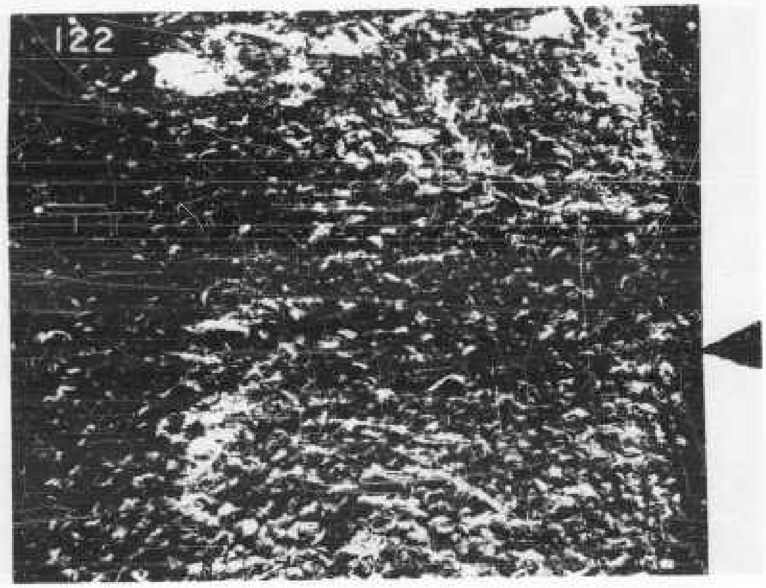

FIGURE 36. FAILURE IN SPECIMEN NO. 122

FIGURE 37. FAILURE IN SPECIMEN NO. 131

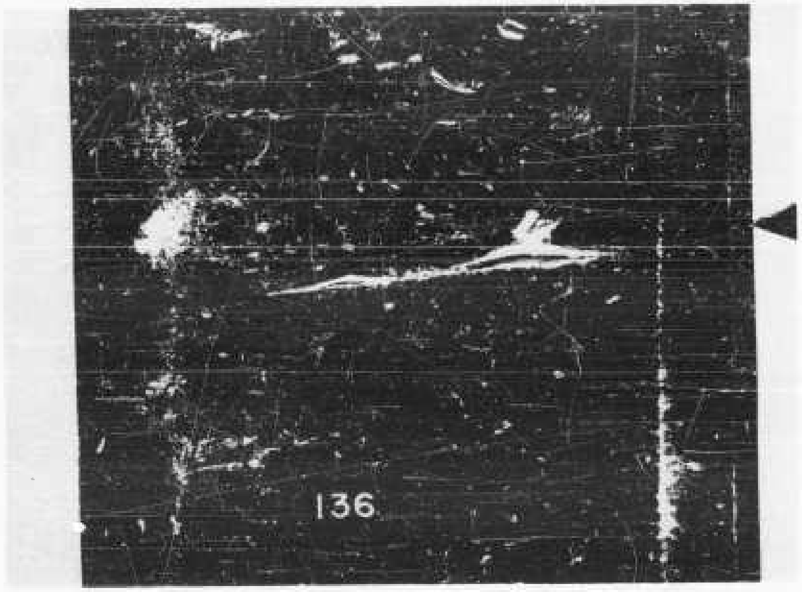

FIGURE 38. FAILURE IN SPECIMEN NO. 136

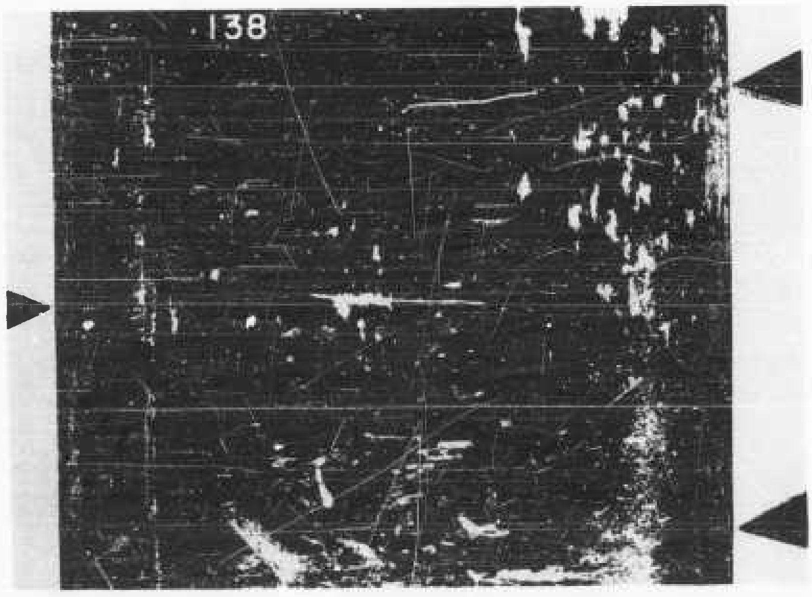

FIGURE 39. FAILURE IN SPECIMEN NO. 138

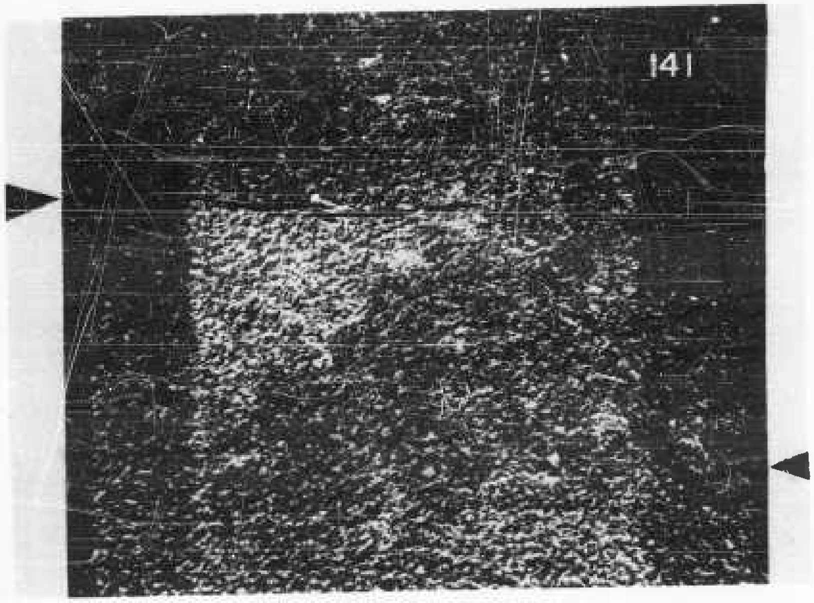

FIGURE 40. FAILURE IN SPECIMEN NO. 141

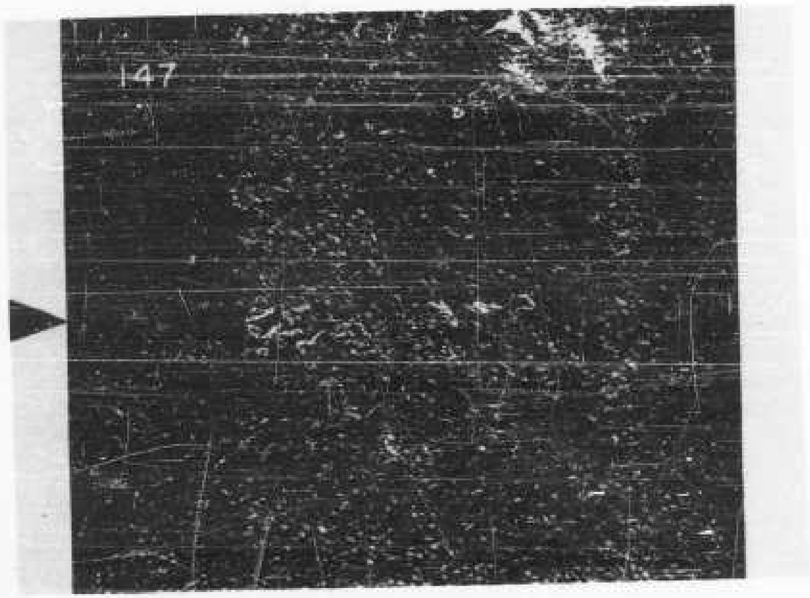

FIGURE 41. FAILURE IN SPECIMEN NO. 147

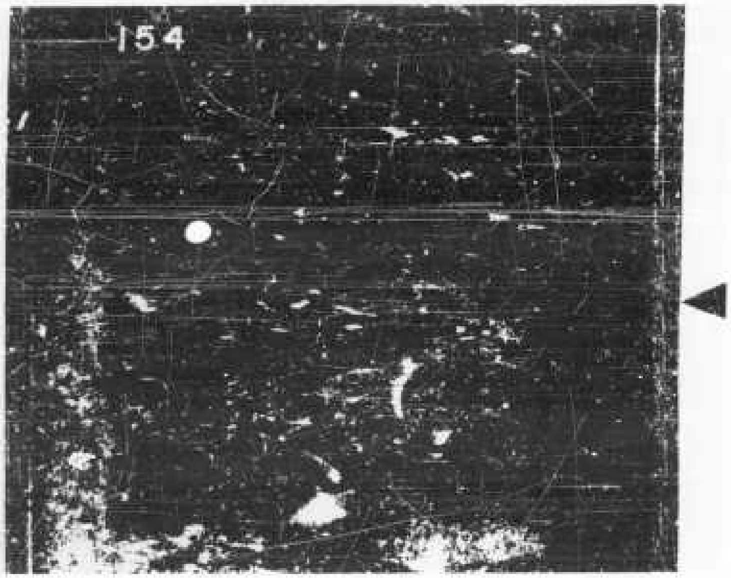

FIGURE 42. FAILURE IN SPECIMEN NO. 154

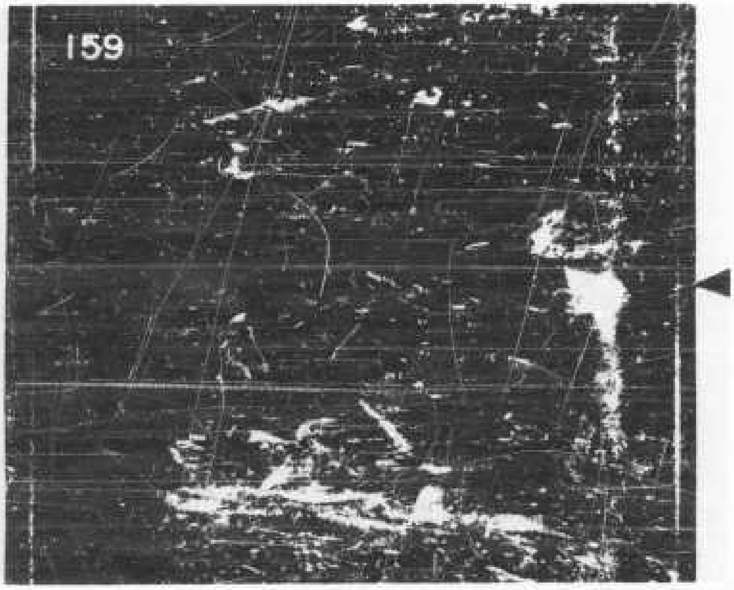

FIGURE 43. FAILURE IN SPECIMEN NO. 159

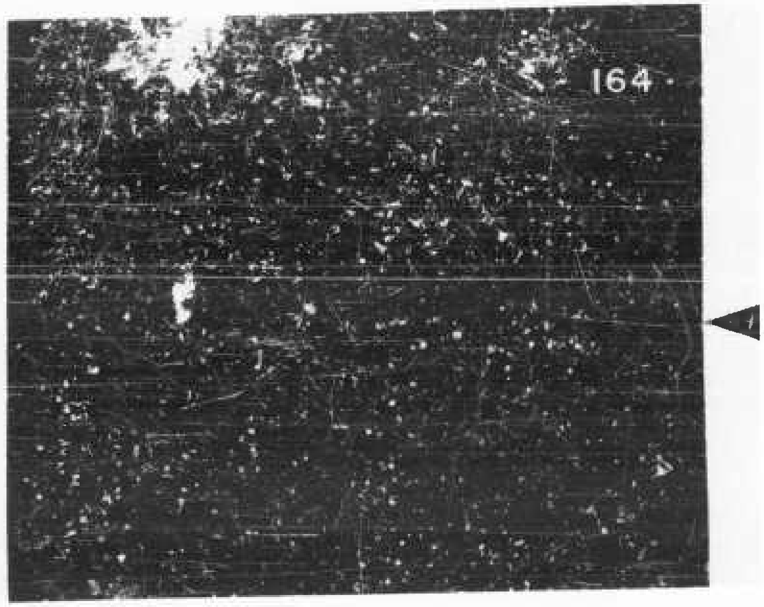

FIGURE 44. FAILURE IN SPECIMEN NO. 164

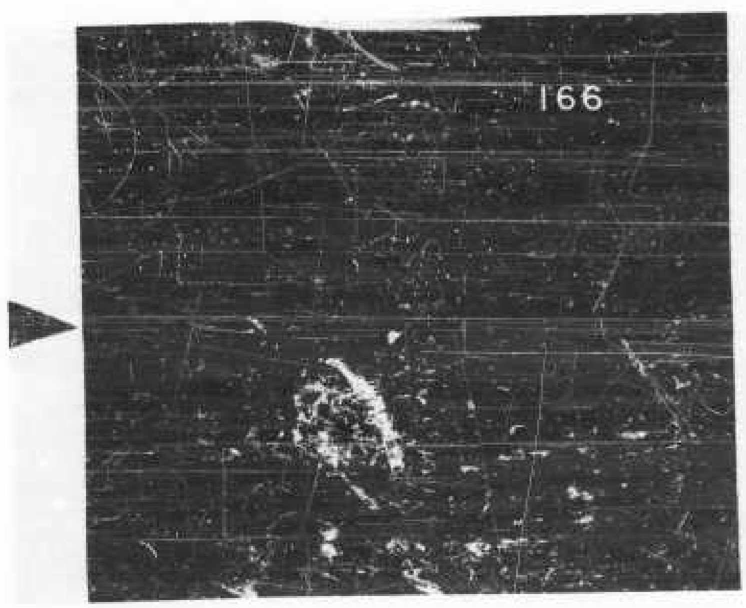

FIGURE 45. FAILURE IN SPECIMEN NO. 166